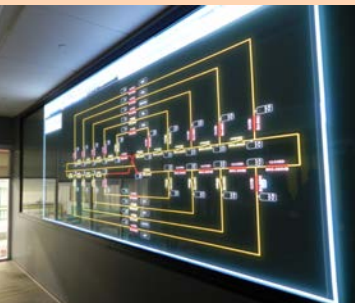


# INNOVATION IMPACT

Breakthrough Research Results







NREL's campus in Golden, Colorado, is a model of sustainable energy and energy efficiency.



# INNOVATION IMPACT



NREL has a rich history of scientific innovation and partnering with industry in research and development to bring new products and technologies into manufacturing production.

In these pages we have captured key breakthrough results across our primary areas of renewable energy and energy efficiency research: solar, wind, bioenergy, transportation, buildings, analysis, and manufacturing technologies.

It is our hope that these examples convey the breadth of research at NREL. Under the stewardship of the Office of Energy Efficiency and Renewable Energy at the U.S. Department of Energy (DOE), NREL is focused on achieving results that have a significant impact on our nation's clean energy goals.

— Dr. Dan E. Arvizu, Laboratory Director



# SOLAR

First Solar Manufacturing Plant, Perrysburg, Ohio, USA

## Launching the World's Largest Manufacturer of Thin-Film Solar Modules

### Innovation

In a long-term collaboration with NREL, an innovator in thin-film solar technology has grown from a startup company to become the world's largest manufacturer of thin-film solar modules. NREL collaborated with First Solar—headquartered in Tempe, Arizona—to develop a manufacturing technology called High-Rate Vapor Transport Deposition, which was essential for the high production rates the company intended to achieve. The process can deposit a thin, uniform layer of cadmium telluride on 8 square feet of glass in less than 40 seconds, and it allowed First Solar's initial production line at its plant in Perrysburg, Ohio, to produce one solar module per minute.

Today, NREL continues to collaborate with solar cell manufacturers through a unique collaborative facility that enables the companies to refine their manufacturing techniques before going into full production.

### Impact

Since it began commercial production, First Solar has produced more than 90 million of its thin-film solar modules, yielding a total capacity of more than 7 gigawatts, enough to power 3.7 million homes. If laid end-to-end, the modules would circle the equator nearly three times. The company uses a continuous manufacturing process that transforms a sheet of glass into a complete solar module in less than 2.5 hours. First Solar currently employs 1,500 people in the United States.



*NREL advances cutting-edge solar cell technologies and partners closely with industry to commercialize them.*



## Quantum Dots Promise to Significantly Boost Photovoltaic Efficiencies

### Innovation

The leading candidate in the search for the next generation of solar-cell technologies is the use of “quantum dots”—tiny spheres of semiconductor material measuring only about 2–10 billionths of a meter in diameter. NREL scientists have produced quantum dots that self-assembled to form a layer of material, which the scientists then integrated into the first-ever quantum-dot solar cell. Although still in the early research phase, NREL’s new device design has the potential to leapfrog existing solar technologies.

### Impact

Quantum dots have the potential to dramatically increase the efficiency of converting sunlight into energy—perhaps even doubling it in some devices—because of their ability to generate more than one charge carrier per incoming photon, compared to only one for today’s solar cells. In addition, varying the size of quantum dots effectively “tunes” them to respond to different wavelengths of light—smaller quantum dots are able to absorb more energetic photons. Thus the same amount of sunlight can be used to generate more electricity.

Using detailed thermodynamic calculations, NREL has shown that quantum-dot solar cells can potentially convert sunlight into electricity at twice the rate achievable by conventional solar cells—converting up to 66% of incident sunlight into electricity.



# WIND



## Partnering with Industry to Design and Test More Efficient Turbines

### Innovation

Wind turbines must withstand powerful aerodynamic forces unlike any other propeller-driven machines. Since the early 1980s, NREL researchers have collaborated with turbine manufacturers to develop many of the technology innovations enabling the success of the wind energy industry.

Among its many contributions, NREL patented and licensed a series of airfoils and an adaptive pitch control system, and helped develop variable-speed turbines, all designed to maximize the efficiency and durability of turbine blades and gearboxes. The laboratory developed a highly accelerated life test to subject turbine gearboxes to 20 years of fatigue damage in only a few months and patented a hydraulic resonance testing system to do the same for turbine blades.

Today NREL continues to test turbines for a variety of leading manufacturers at DOE's National Wind Technology Center located at the laboratory's wind site near Boulder, Colorado.

### Impact

The technological innovations pioneered by NREL and its industry partners have resulted in more efficient and durable wind turbines and a dramatic reduction in the cost of wind energy.

One of the start-up manufacturers collaborating with NREL was acquired by General Electric. GE incorporated the improvements in its first multi-megawatt turbines, including the widely deployed 1.5-megawatt model, with more than 16,500 turbines installed globally.



*NREL and its manufacturing partners pioneered many of the innovations leading to today's robust wind industry.*



## Researching Power Plant Dynamics to Improve Production and Reliability

### Innovation

With the emergence of utility-scale wind power plants, the next great research challenge is maximizing the efficiency and durability of large installations incorporating dozens of turbines. Massive wind turbines in close proximity create wake turbulence that can degrade performance and damage adjacent turbines. NREL researchers are using infrared radar and other sensitive instruments to measure the effects of turbulence to improve wind turbine design and the siting of turbines within wind plants.

NREL scientists have also developed complex software models to predict the effects of downstream turbulence on turbine blade structures, gearboxes, and drivetrains. One NREL-designed tool couples a computational fluid dynamics calculator with a turbine simulator, allowing highly advanced evaluation of the effects of turbulence on power production and loading of upstream and downstream turbines.

### Impact

Incremental improvements in efficiency can significantly impact wind power plant electricity production. The potential exists for a 5%–10% increase in energy capture through wake control, optimum turbine placement, and individual turbine adjustment in real time.

This complex research —vital to industry growth—will yield information critical to extending turbine lifecycles, improving power plant performance, and reducing the cost of wind energy to make it even more competitive with other sources of electricity.



# BIOENERGY



## Proving that Cellulosic Ethanol can be Cost Competitive

### Innovation

Ethanol produced from non-food plant sources, called “cellulosic ethanol,” can potentially replace 30% of our nation’s petroleum consumption. But can it do so at competitive prices? Through a multi-year research project involving private industry, NREL has proven that cellulosic ethanol can be cost-competitive with other transportation fuels. NREL demonstrated the technical advances needed to produce cellulosic ethanol at a minimum ethanol selling price of \$2.15 per gallon.

After several years of modeling, performing biomass-to-fuels conversion test runs, and compiling and analyzing market data, NREL showed that realistic production scenarios could meet the \$2.15 per gallon goal, established by DOE to prove that cellulosic ethanol could be competitive with corn ethanol and conventional fuels.

### Impact

The models developed by NREL have enabled private industry to ramp up efforts to commercialize cellulosic ethanol production. Facilities to produce cellulosic ethanol are under construction across the country, including DOE-supported projects led by Abengoa in Hugoton, Kansas; POET in Emmetsburg, Iowa; and INEOS in Vero Beach, Florida. Industry and DOE are also leveraging the research to commercialize other technologies for biomass conversion, including converting cellulosic feedstocks into drop-in biofuels that are compatible with existing infrastructure and nearly indistinguishable from gasoline, diesel, and jet fuel.



*NREL is a leader in cellulosic ethanol research for blended fuels and in next-generation “drop-in” biofuels.*



## NREL Co-Leads a Consortium to Advance “Drop-In” Biofuels

### Innovation

As a follow-up to its success with cellulosic ethanol, NREL has turned its attention to the next generation of biofuels: so-called “drop-in” biofuels that function just like crude oil or any of today’s major petroleum fuels, allowing them to be easily incorporated into the existing fuel infrastructure. NREL and the Pacific Northwest National Laboratory are co-leading the National Advanced Biofuels Consortium (NABC), a three-year effort to winnow down the list of possible biomass conversion technologies and to prepare one or two processes for scale-up to the pilot scale, a critical step for commercializing the process.

### Impact

The NABC investigated six process options for creating drop-in biofuels and narrowed the list to two main processes: fermentation, which can be used to produce diesel fuel; and the catalytic conversion of sugars to fuels, which can produce all three major transportation fuels. The NABC will soon complete its work to prepare these technologies for the pilot scale, including detailed engineering studies and environmental impact analyses. In addition, the NABC is working to address the main technical challenges faced by two additional processes: hydrothermal liquefaction and hydrolysis, both of which are aimed at producing crude oil substitutes.



# TRANSPORTATION



## Tools to Design Better Electric Vehicle Batteries

### Innovation

While electric vehicles (EVs) promise to curb greenhouse gas emissions and slash America's need for imported oil, the design of high-performance, cost-effective, and safe batteries has proven challenging. NREL is leading teams of automakers, battery developers, and other research institutions in developing the sophisticated software tools needed to create batteries for next-generation EVs. Modeling tools created by the Computer-Aided Engineering for Electric Drive Vehicle Batteries (CAEBAT) team will improve and accelerate battery design and production, boost EV performance and consumer appeal—and ultimately diminish energy use and emissions.

### Impact

According to projections by the DOE's EV Everywhere challenge, EVs will have difficulty gaining meaningful market share until batteries can deliver the 280-miles-per-charge range drivers expect. At the same time, battery costs need to be cut by about 75% (to \$125/kWh) to make EVs more competitive with gasoline-fueled vehicles. The CAEBAT suite of battery cell and pack engineering tools is formulated to:

- Shorten battery prototyping and manufacturing processes
- Improve overall battery performance, safety, and lifespan
- Reduce costs for manufacturers and consumers

Convinced of the need for and promise of these software tools, General Motors and Ford Motor Company have joined NREL on the project team.



*NREL collaborations with industry deliver solutions to balance vehicle energy savings and emissions reductions with performance.*

A thermal map of a vehicle interior, showing temperature variations across the cabin. The map uses a color scale from blue (cooler) to red (warmer). A white crosshair is visible in the upper center of the image.

## Thermal Management for Optimal Vehicle Performance

### Innovation

Regulating battery and power electronic system operating temperatures, along with effective climate control, is imperative to optimizing vehicle performance, lifespan, and affordability. NREL's innovations in modeling, simulation, and testing pinpoint thermal performance issues to enable the design of more efficient and reliable passenger and commercial vehicles.

### Impact

Extreme temperature swings can dramatically impact the performance and reliability of EV batteries and power electronic components. NREL's R&D 100 Award-winning Isothermal Battery Calorimeters are the only instruments in the world capable of the precise thermal measurements needed to design longer-lasting, safer, and more affordable batteries. Novel thermal management technologies developed by NREL researchers for power electronics and motors are helping to reduce cost and increase reliability of these components. Climate control is also critical. Long-haul trucks idling during rest stops consume 838 million gallons of diesel fuel annually in the United States, mostly for heating and air conditioning. Working closely with industry partners, NREL has applied its modeling tools, CoolCalc and CoolSim, to demonstrate the potential for a 34% reduction in these climate-control loads. In light-duty EVs, where climate-control loads can cut the driving range in half, NREL is also researching techniques to significantly reduce air conditioning and heating requirements.



# BUILDINGS



## NREL Building Innovations Enable a Living Laboratory for Energy Efficiency

### Innovation

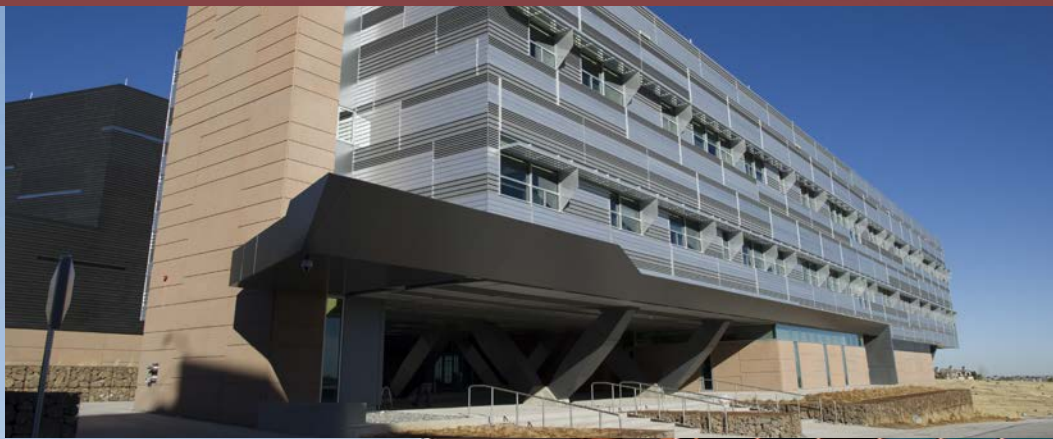
Creating a “net-zero” energy building, which produces as much energy as it consumes, requires a comprehensive approach to design and construction. NREL engineers collaborated with architects and construction firms to integrate cutting-edge efficiency innovations into the laboratory’s Research Support Facility (RSF). The highly efficient, 360,000-square-foot building benefits from many NREL innovations, such as “transpired” solar collectors that passively preheat outside air to save on heating costs. Another NREL innovation, electrochromic window glazing, electronically adjusts window tinting to control interior daylighting and heat gain. To offset its energy use, the RSF taps 1.6 megawatts of solar power from its rooftop and nearby parking structures.

### Impact

Americans spend \$400 billion annually to power homes and commercial buildings, though an estimated \$80 billion could be saved through energy efficiency. Improving efficiency will significantly reduce energy demand. The RSF, designed as a net-zero-energy building, uses 50% less energy than if it were built to current commercial code, serving as a model for others to follow. Since the facility opened in 2010, hundreds of architects, designers, construction engineers, and national, state, and local officials have toured the building and taken part in energy efficiency workshops, learning how to replicate the RSF’s high-performance design approach.



*NREL software modeling and efficiency innovations laid the foundation for net-zero-energy buildings.*



## Software Modeling Platform Enables Building Industry to Adopt Efficient Designs

### Innovation

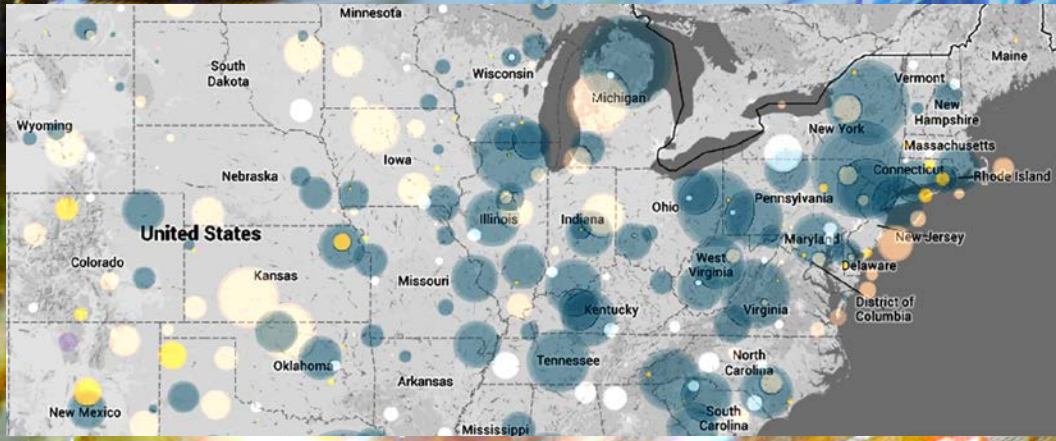
NREL's building energy research has led to more stringent building energy codes, making it critical for designers to incorporate efficiency in their buildings from the start. To assist the designers, NREL engineers have developed a sophisticated energy modeling and analysis software system that enables energy efficiency to be considered in the early design phases. Freely available for commercial use, OpenStudio works with building design software to simplify whole-building modeling and simulation, which is the key to creating cost-effective, energy efficient buildings. OpenStudio tools make consideration of energy-saving technologies like efficient windows, lighting, and heating and cooling systems "drag-and-drop easy" for design professionals, who struggle daily with time and budget pressures on their projects.

### Impact

OpenStudio makes energy modeling more accessible. Since its launch in 2010, it has attracted more than 12,000 registered users, and has become widely adopted by both government and industry. Funding from non-DOE sources for OpenStudio development and support has grown from 10% to almost 50% over the last three years, reflecting its value to the private sector and other state and federal agencies. In fact, many utilities are adopting OpenStudio to help identify energy-saving approaches in new construction and building retrofits, determining which measures qualify for energy-efficiency incentive programs.



# ANALYSIS



## Energy Models Provide the Foundation for Groundbreaking Analytical Reports

### Innovation

Rapid deployment of renewable energy raises complex questions, such as “How will our grid infrastructure accommodate increasing amounts of renewable energy?” Fortunately, NREL has a 30-year history of developing analytical models to address such questions. For electricity generated from renewable energy, for instance, NREL analysts use the geographic information system-based Regional Energy Deployment System (ReEDS) to explore the U.S. electric sector across multiple regions and time periods.

### Impact

NREL’s world-class modeling capabilities have underpinned several groundbreaking technical reports. For example, the Western Wind and Solar Integration Study demonstrated that the western power grid could draw on wind and solar energy for 35% of its electricity by 2017. Likewise, the Eastern Wind Integration and Transmission Study found that the eastern and central United States could rely on wind power for 20% of its electricity by 2024. ReEDS was integral to NREL’s Renewable Electricity Futures Study, which found that renewable technologies that are commercially available today, in combination with a more flexible electric system, can supply 80% of total U.S. electricity generation in 2050 while meeting electricity demand on an hourly basis in every region of the country.

Such studies help to illuminate what is possible and provide critical guidance for energy policymakers and investors.



*NREL's sophisticated energy models and open energy data platform enable innovative analysis that informs investment and policy decisions.*



## Creating a Global Analytical Repository for Energy Data and Information

### Innovation

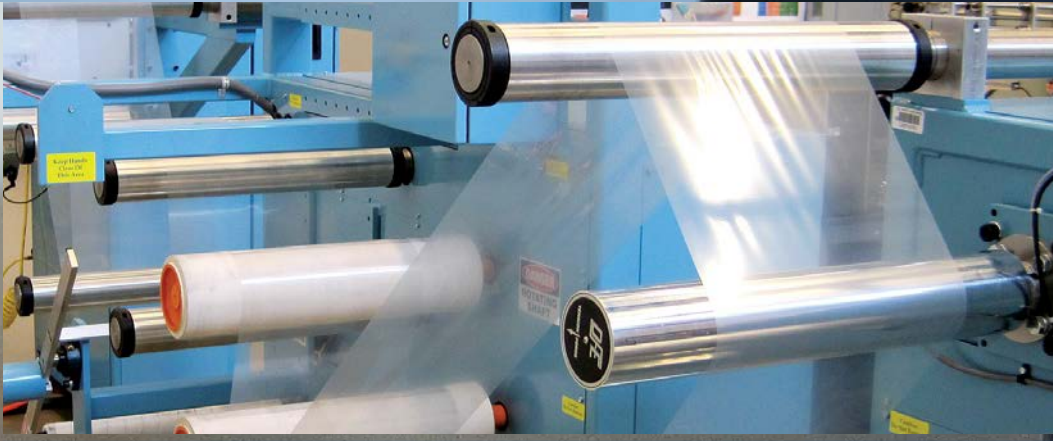
A vast amount of energy-related data is generated throughout the world, but historically, access to this data has been difficult and limited. To address this issue, NREL analysts created a collaborative Web platform called OpenEI. Managed by NREL for DOE, OpenEI facilitates access to data and empowers the energy community to use and contribute to the collection. It links energy communities including policy makers, researchers, technology investors, venture capitalists, and market professionals with valuable energy information, analyses, tools, images, maps, and other resources. NREL developed OpenEI in support of the Open Government Initiative to bring the power of “crowdsourcing”—the harnessing of collective brainpower to tackle problems—to the energy sector.

### Impact

OpenEI has become a recognized leader in the energy data sector. In one month alone, more than 55,000 visitors from nearly 200 countries used OpenEI synthesis and visualization tools to analyze energy information. Data quality is ensured by users and NREL content experts who have contributed more than 640,000 edits to the content since the launch of OpenEI in 2009. OpenEI is a unique asset, providing the energy community with improved analyses and real-time access to data.



# MANUFACTURING



## New In-Line Diagnostics Show Promise for Cutting Hydrogen Fuel Cell Costs

### Innovation

Hydrogen fuel cells could one day power our vehicles and heat and power our buildings, but their deployment is limited by their high cost, caused partly by low production volumes. To help industry transition to high-volume production, NREL is developing in-line diagnostic tests for fuel cell components, including an optical system that can measure the thickness of a membrane over a large area and detect any defects. NREL is also using thermal imaging techniques to lower manufacturing costs by detecting early defects in electrode material.

### Impact

NREL's diagnostic techniques are expected to significantly lower costs for hydrogen-powered fuel cells, while also leading to tighter production tolerances. Researchers are validating these processes on a small-scale manufacturing line in NREL's Energy Systems Integration Facility, a DOE National User Facility. The demonstration line can convey fuel cell component materials at speeds of 100 feet per minute.

The cost impacts of defects could be huge: a fuel cell "stack" could consist of hundreds of components, and because a single component failure could affect the whole stack, a 10% failure rate is estimated to drive up the stack cost by 60%.



***NREL develops and tests diagnostic tools and manufacturing techniques that can reduce the cost of producing clean energy devices.***



## Award-Winning Etching Process Cuts Solar Cell Costs

### Innovation

A key to producing high-efficiency solar cells is ensuring that most of the sunlight that hits the cell is absorbed, rather than reflected. Today's solar cell manufacturers use complicated, time-consuming, and expensive methods of etching cell surfaces and applying anti-reflective coatings. To address this issue, NREL scientists have developed an inexpensive chemical etch that will provide similar benefits quickly and at much lower manufacturing cost. The technique, called "black silicon" for how it darkens the solar cell, won an R&D 100 Award in 2010 from *R&D Magazine*, recognizing it as one of the top 100 inventions of the year. Long sought after by solar researchers, the black silicon achievement demonstrates NREL's extensive research capabilities.

### Impact

Natcore Technology Inc., based in Red Bank, New Jersey, has licensed NREL's etching technology and is incorporating it into its proprietary manufacturing process for solar cells. Natcore, a startup company, is investing nearly \$2 million in a research facility in Rochester, New York. NREL expects its black silicon process to boost solar cell efficiencies, and the cells' improved performance at low sun angles should boost energy generation by 1%-3%. Considering the tight margins in today's solar industry, such small gains could provide an essential competitive advantage for solar cell manufacturers.





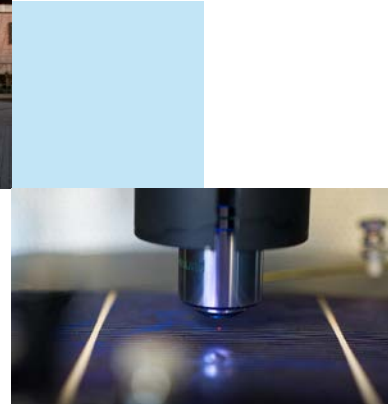


*For more than 35 years, NREL has delivered innovation impact enabling the emergence of the U.S. clean energy industry. For more information please visit our website at [www.nrel.gov](http://www.nrel.gov).*



*Image credits: front cover, from left to right, photo by Kim Adams, NREL 24927, photo by Dennis Schroeder, NREL 19119; photo by Lee Jay Fingersh, NREL 22073; page 2-3: photo background by Dennis Schroeder, NREL 25803; photo inset by Dennis Schroeder, NREL 26240; page 4-5: photo inset left from First Solar Manufacturing Plant, Perrysburg, Ohio, USA; photo inset right by Dennis Schroeder, NREL 19884; page 6-7: photo inset left by Dennis Schroeder, NREL 21869; photo inset right by Christian Steiness, Vattenfall Wind Power Denmark; page 8-9: photo inset left by Dennis Schroeder, NREL 17879; photo inset right by Dennis Schroeder, NREL 19549; page 10-11: illustration inset left by Josh Bauer, NREL; photo inset right by Ken Proc, NREL 16812; page 12-13: photo inset left by Dennis Schroeder, NREL 22290; photo inset right by Dennis Schroeder, NREL 23704; page 14-15: photo background, iStock 2329036; photo inset right by Kevin Eber, NREL 26452; page 16-17: photo inset left by Michael Ulsh, NREL 18309; photo inset right by Dennis Schroeder, NREL 17852; page 18-19: photo background by Dennis Schroeder, NREL 25929; back cover photos by Dennis Schroeder, NREL 18297, NREL 19758, NREL 17820, NREL 18967*





For more information please visit our website at [www.nrel.gov](http://www.nrel.gov).



National Renewable Energy Laboratory  
15013 Denver West Parkway, Golden, CO 80401  
303-275-3000 • [www.nrel.gov](http://www.nrel.gov)

NREL is a national laboratory of the U.S. Department of Energy  
Office of Energy Efficiency and Renewable Energy  
Operated by the Alliance for Sustainable Energy, LLC

NREL/BR-6A42-58599 • July 2013

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