INITIATIVE FOR RENEWABLE ENERGY & THE ENVIRONMENT

2011 ANNUAL REPORT

INSTITUTE ON THE ENVIRONMENT

UNIVERSITY OF MINNESOTA
Driven to Discover℠

IREE'S MISSION: TO PROMOTE STATEWIDE ECONOMIC DEVELOPMENT; SUSTAINABLE, HEALTHY AND DIVERSE ECOSYSTEMS; AND NATIONAL ENERGY SECURITY THROUGH DEVELOPMENT OF BIO-BASED AND OTHER RENEWABLE RESOURCES AND PROCESSES.

On the cover: **Fotis Sotiropoulos,** professor of civil engineering in the College of Science and Engineering and director of the St. Anthony Falls Laboratory

BRINGING SUSTAINABLE ENERGY TO MARKET

A BRIGHTER ENERGY FUTURE BEGINS WITH IMAGINATIVE RESEARCH SUPPORTED BY SUFFICIENT FUNDING TO TURN VISION INTO REALITY. BUT IT DOESN'T END THERE. MOVING INNOVATIVE IDEAS TO MARKET IS AN IMPORTANT PART OF BRINGING SUSTAINABLE ENERGY TO LIFE. PARTNERSHIPS MAKE IT POSSIBLE.

Commercializing clean, sustainable domestic energy is one of America's most pressing challenges. A program of the University of Minnesota's Institute on the Environment, the **Initiative for Renewable Energy and the Environment** (IREE) seeks out the most promising new renewable energy ideas and brings them to life with support from Xcel Energy ratepayers via the utility's Renewable Development Fund.

More affordable photovoltaic energy, better batteries, improved household energy conservation, renewable jet fuel and power-producing bacteria—a lot of promising research into clean, renewable energy is happening here at the University of Minnesota because of IREE. This year, IREE has invested $4.1 million in a variety of projects to find new ways to produce clean, renewable energy and other products. These projects are an investment in a secure national energy future and a cleaner environment. IREE-funded research is also a sound investment in Minnesota's economy, education and potential business start-ups. IREE grants are invested in Minnesota's human capital to advance renewable energy technology.

To make sure the benefits of research spread to the community and economy, IREE has encouraged partnerships with companies, trade associations, and government—groups such as 3M, the Minnesota Corn Growers Association, the Metropolitan Council and many more. Teaming up with these kinds of partners not only multiplies IREE's research funds several times over, it also informs the research and ensures that successful products and processes enter the marketplace as quickly as possible.

IREE funds other opportunities for outreach to the world—conferences, meetings, forums, presentations and other events that bring together energy experts, innovators and leaders. Our goal: to fund research that builds a brighter future, a cleaner environment and a stronger Minnesota.

PARTNERSHIPS

IREE GRANTS BUILD PARTNERSHIPS WITH RESEARCHERS IN UNIVERSITIES, PRIVATE INDUSTRY AND NATIONAL LABORATORIES TO BETTER FUND RESEARCH OPPORTUNITIES, BRING GREATER EXPERTISE TO PROJECTS AND SPEED THE PROCESS OF BRINGING SUCCESSFUL PRODUCTS AND PROCESSES TO MARKET. THE RESULTS ARE NEW KNOWLEDGE, SOLUTIONS, BUSINESSES AND JOBS.

MINNESOTA CORN GROWERS

Agriculture provides great promise for providing new renewable biofuels. And increased biofuel production could provide added income for farmers while benefiting local economies. For both those reasons, IREE and the Minnesota Corn Growers Association established a partnership two years ago to plan and fund research into renewable energy strategies. "World-class researchers in a world-class institution—I'd like to think we help each other," says Tim Gerlach, Corn Growers executive director. "I guess that's the definition of a partnership. "

CENTER FOR SUSTAINABLE POLYMERS

IREE recently teamed with the University's new Center for Sustainable Polymers to develop environmentally friendly, advanced polymers to replace plastics, rubber and adhesives derived from fossil fuel. The center just won a three-year National Science Foundation grant. IREE's support was absolutely critical for the successful grant application," says center director and chemistry professor Marc Hillmyer. "The IREE resources provided the seed, fertilizer and water to grow the center from nothing to a full-functioning center of excellence for research in sustainable polymers."

EOLOS WIND ENERGY RESEARCH CONSORTIUM

IREE helped the University land a Department of Energy grant to form the Eolos Wind Energy Research Consortium. This group of universities, national labs and industrial partners (including local firms WindLogics, 3M and Barr Engineering) are tackling cutting-edge issues in wind farm and turbine design. "IREE does that matchmaking," says Jeff Marr, associate director of Eolos. "They bring industry leaders together with University researchers and create a chance to talk, to meet and to brainstorm about how we can work together."

METROPOLITAN COUNCIL

IREE's collaboration with the Metropolitan Council has been fertile, figuratively and literally. University researchers raised algae in wastewater to remove nutrients and provide a potential source of biofuels. The "super bus" project aims to boost mileage of Metro Transit buses by more efficiently supplying power to accessories such as air conditioning. "Part of what we do is anticipate challenges and assemble the right people in analyses that provide management with options, regardless of boundaries between organizations," says Jason Willett, financial management director for Metropolitan Council Environmental Services.

3M SOLAR ENERGY PARTNERSHIP ▶

IREE funding and networking established a partnership with 3M to test the use of a new light-selective mirrored film to improve the efficiency of solar photovoltaic and solar thermal power generation. "When they developed this film they were thinking, 'Who can help us develop products that can use it effectively?'" says Jane Davidson (pictured right), professor of mechanical engineering. IREE provided a grant to get started. "IREE funding is really what's allowing us here at the University to work with 3M."

OUTREACH

DON'T UNDERESTIMATE THE IMPORTANCE OF PUBLICIZING ACCOMPLISHMENTS AND ESTABLISHING RELATIONSHIPS WITH OTHER RESEARCHERS AND INSTITUTIONS. IREE'S BEHIND-THE-SCENES WORK HAS MADE THE UNIVERSITY OF MINNESOTA MORE VISIBLE ON THE RENEWABLE ENERGY SCENE AND FOSTERED IMPORTANT SCIENTIFIC COLLABORATION.

E3—IREE'S ANNUAL SHOWCASE

E3, IREE's annual November conference, is a showcase of current technologies, environmental benefits and market opportunities in renewable energy. Last year, more than 650 attendees from business, universities and government heard some 75 speakers, including Daniel Kammen, chief technical specialist for renewable energy and energy efficiency at the World Bank. E3 is one of IREE's most effective ways of building partnerships in business and industry and positioning Minnesota as a hub of innovation.

GLOBAL SUSTAINABLE BIOENERGY CONVENTION

IREE funding enabled the University's Institute on the Environment to host the fifth of five continental conventions of the Global Sustainable Bioenergy Project, a worldwide collaboration of universities and institutes to envision a path to large-scale use of bioenergy. Co-chairs of the September 2010 meeting were Jon Foley, director of the Institute on the Environment, and John Sheehan, science director at IREE.

ALGAE BIOMASS SUMMIT

Nearly 900 industry professionals from the world's algae utilization industries met in Minneapolis in October for the fifth annual Algae Biomass Summit. Organized by the Algal Biomass Organization and co-hosted by IREE, the four-day summit brought together researchers, project developers, utility executives, venture capitalists and policy makers to seek out viable technologies and markets for renewable products derived from algae, including biofuels, animal feeds, fertilizers, plastics and food.

ST. ANTHONY FALLS LAB HYDROPOWER SOLUTIONS ▶

Officials and researchers from the National Science Foundation, DOE, national labs including Sandia and Oak Ridge, and

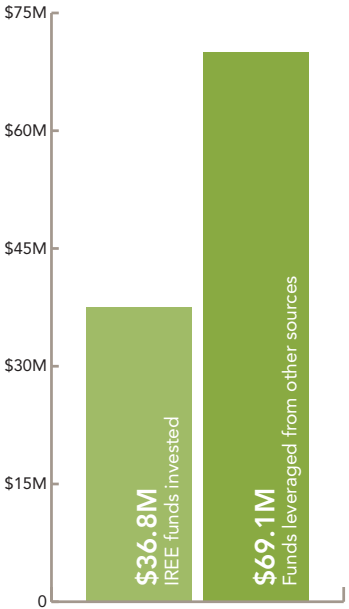
several U.S. universities came to the University's St. Anthony Falls Laboratory for a research workshop on marine and hydrokinetic energy and the environment, aided with an IREE grant. The St. Anthony Falls Lab's unique facilities on the Mississippi River (pictured right) have positioned it to advance these new-generation hydropower technologies, which have the potential to harness waterpower with minimal harm to the environment.

WORLDWIDE THERMAL STORAGE EXPERTS

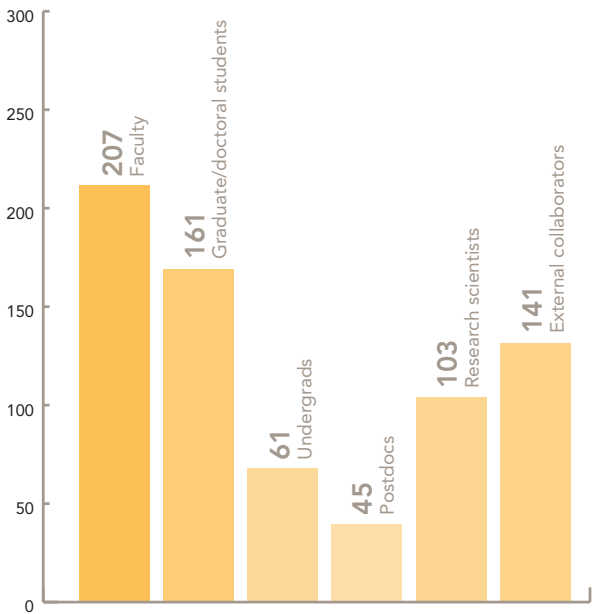
IREE support helped the International Energy Agency Task Force on Thermal Storage meet at the University in September. These energy experts are developing new methods to store energy derived from renewable sources, says Jane Davidson, director of mechanical engineering and U.S. representative to the group. "We publish our papers in scientific journals and we go to conferences, but there's a big difference between doing that and having three days of having one-to-one conversations with the world's leading experts."

FACTS & FIGURES

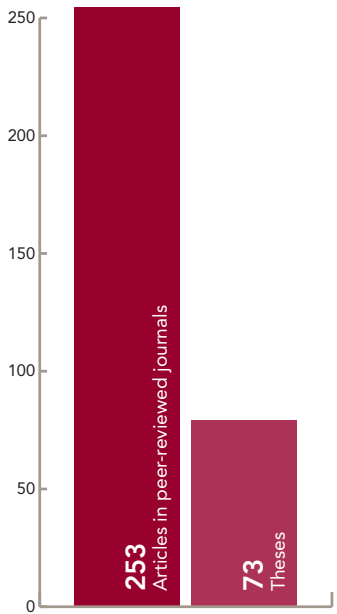
FINANCES



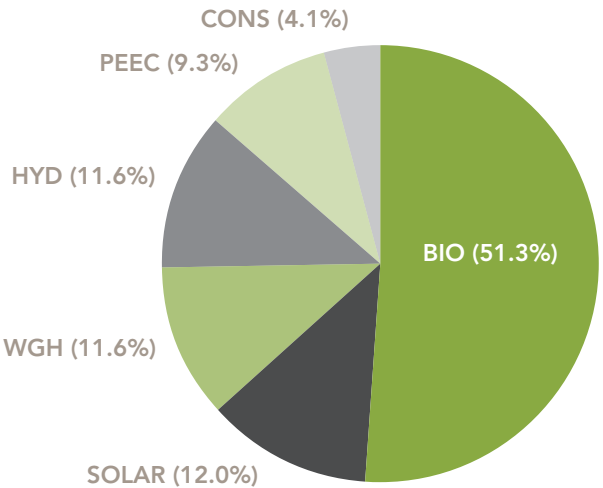
PERSONNEL



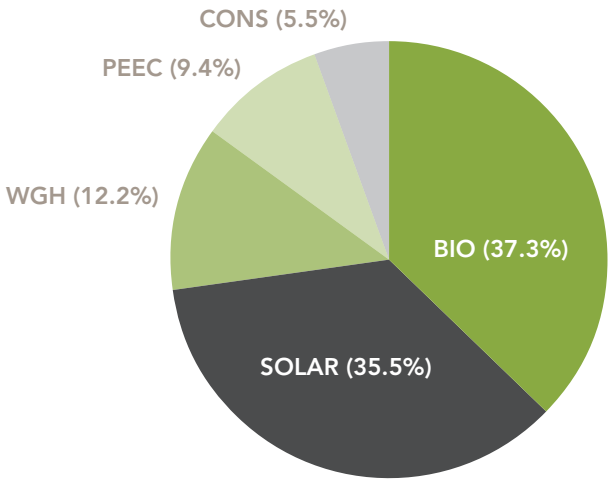
PUBLICATIONS



INVESTMENTS BY CATEGORY (FY04-FY08)



INVESTMENTS BY CATEGORY (FY09-FY12)



BIO: BIOENERGY & BIOPRODUCTS, SOLAR: SOLAR, PEEC: POLICY, ECONOMICS & ECOSYSTEMS,
CONS: CONSERVATION & ENERGY EFFICIENCY, WGH: WIND, HYDRO & GEOTHERMAL, HYD: HYDROGEN PRODUCTION, STORAGE & USE

RESEARCH OVERVIEW

SINCE 2003, IREE HAS AWARDED NEARLY $37 MILLION TO 242 RESEARCH EFFORTS, ADVANCING INNOVATION AND APPLICATION IN SIX KEY AREAS:

- BIOENERGY & BIOPRODUCTS
- CONSERVATION & ENERGY EFFICIENCY
- SOLAR
- WIND, HYDRO & GEOTHERMAL
- POLICY, ECONOMICS & ECOSYSTEMS
- HYDROGEN PRODUCTION, STORAGE & USE

Large grants provide significant funding for comprehensive projects with strong potential to be energy game-changers. Seed grants support high-risk, high-potential exploratory research, helping move bright ideas forward to the point where researchers can evaluate their promise and pursue additional funding. Early career grants offer support for University faculty just beginning work in the field of renewable energy. IREE's special opportunity program provides dedicated funding to strategically targeted areas of investment. Matching grants leverage research investments from other sources including federal agencies such as DOE, NSF, the U.S. Department of Agriculture and the Department of Defense. In some cases the IREE matching funds provides needed cost-share dollars that may provide a competitive advantage for the project.

IREE takes a systems-based approach that integrates scientific,

economic and environmental perspectives. IREE-funded projects have tapped the breadth and depth of expertise at the University of Minnesota, including seven colleges, five campuses and three research and outreach centers. To date, over 575 researchers at the University and close to 150 external collaborators have been engaged in IREE-supported research.

IREE provides funding for promising technologies. We also work with academic and industrial partners to overcome roadblocks that keep potentially useful and profitable technologies from succeeding in the marketplace.

IREE-funded research spans the spectrum from basic science to commercial application. Some projects pay dividends almost immediately; others lay the foundation for tomorrow's innovation.

IREE funds a variety of research areas rather than a few specific technologies. Our solar portfolio, for example, includes unleashing the power of concentrated solar, hot-water heating and space conditioning, novel photovoltaic films, innovative storage systems, nanotechnology, and conversion of mining "waste rock" into passive solar walls.

IREE pursues the conventional and novel. A project with Xcel Energy to integrate a super-battery into wind energy production is a straightforward attempt to overcome the limitations of wind power. Other IREE projects take more unexpected approaches—for example, converting wind power into ammonia, a renewable nitrogen fertilizer and potentially useful fuel in the agricultural regions where wind farms are located.

IREE looks for multiple benefits in research projects—a potential one-two punch in commercial application. A prime example is a partnership to grow oil-rich algae in the wastewater moving through the Metropolitan Wastewater Treatment Plant. Thriving algae not only yield oil for fuel, but also suck up nutrients to help the facility meet increasingly stringent water quality standards.

IREE strives to find practical solutions to energy-related challenges and to make the University of Minnesota the go-to place for renewable energy research. The following pages showcase just a few of the projects that exemplify these aims.

GROWING FOOD *AND* FUEL WITH WHEATGRASS

DEVELOPING INTERMEDIATE WHEATGRASS FOR SUSTAINABLE CO-PRODUCTION OF FUEL AND FOOD, $695,000

Most major food crops are annuals. The yearly cycle of harvesting and growing new plants can lead to challenges: release of soil carbon, inputs of fossil fuel–based fertilizer and soil erosion.

With seed money from IREE, **Donald Wyse,** professor of agronomy and plant genetics in the College of Food, Agricultural and Natural Resource Sciences, is breeding and testing intermediate wheatgrass, a long-lived perennial cousin to wheat, rye and barley. "It has the potential to become the first perennial crop where straw is used for biofuel and seed is used for grain," says Wyse. A perennial grain-biofuel crops, he says, would have "profound implications"—less need for fertilizer, a greater yield in bioenergy than would be required to grow the crop, and increased value for the farmer. "You really get a three-for," says Wyse. "It's grain for food, it's the biomass for energy and it's a valuable ecosystem service."

Wyse is relying on interdisciplinary research within the College of Food, Agricultural and Natural Resource Sciences to breed wheatgrass through both classical and modern molecular methods to increase yield and performance in northern climates. Through agronomic experiments, researchers will determine the impacts of genetics, fertilizers and legume intercropping on carbon sequestration, biomass yield, seed yield, flour quality and profitability. The University effort is part of a federal program on cereals. Says Wyse, "So IREE's investment helps us leverage this major federal resource."

DESIGNING A BETTER WIND TURBINE

The DOE has set a goal to generate 20 percent of its electricity by wind by 2030. To meet that objective, wind turbines must become more efficient, more reliable, more economical and less obtrusive. The Eolos Wind Energy Research Consortium—led by St. Anthony Falls Laboratory in the College of Science and Engineering—is tackling these challenges "to accelerate—that's the key word—the advancement of wind technology in the United States," says **Jeff Marr,** Eolos' associate director.

The consortium, which includes universities, colleges, national labs and industry partners, operates with DOE support, matched by funds from University sources, including IREE. To enable testing, demonstration, and data collection, Eolos is constructing a Rosemount research field station with a 415-foot-tall Clipper Windpower 2.5 megawatt turbine.

University researchers, working with industrial partners, are experimenting with blade surfaces and "smart-blade" technologies to reduce drag and capture more of the wind's energy. New computer models better represent airflow over blades for better design and performance. Advanced computer modeling identifies optimum wind-farm sites and design to reduce energy-sucking turbulence between turbines.

New turbine monitoring approaches promise to improve turbine performance and lower maintenance costs. Eolos researchers are trying to prevent ice build-up, which can damage equipment, and minimize radar interference.

Finally, Eolos is using the opportunity of its concentrated research to train the next generation of wind industry engineering leaders through new classes and curricula at the University and other institutions.

A CONSORTIUM FOR ACHIEVING 20% WIND BY 2030 THROUGH CUTTING-EDGE RESEARCH AND WORKFORCE TRAINING, $400,000

SPREADING ENERGY SAVING TO OLDER HOMES

Home heating, cooling and lighting are huge energy uses. For two decades, the DOE has brought energy-saving technologies to home construction.

But here's the problem: Those aren't the homes most of us live in.

"If you look at 2030 or even 2050, the houses that are going to be there, most of them are already built," says **Pat Huelman,** associate professor of bioproducts and biosystems engineering in the College of Food, Agricultural and Natural Resource Sciences and co-leader of the University's NorthernSTAR Energy Efficient Housing Research Partnership.

"We've got to figure out how to fix the ones that are currently here, bring them up to much higher levels of energy performance."

That's the chief challenge of NorthernSTAR, an industry-driven research program sponsored by the DOE and designed to accelerate the adoption of energy-saving technologies. NorthernSTAR, one of 15 teams nationwide, will devote more than 60 percent of its resources to existing homes. Says Huelman, "IREE is providing a really important matching pool of money so we can leverage the DOE resources."

Owners of existing homes are looking for quick payback of their expenses. As a result, NorthernSTAR is looking for two-for-one improvements that both save energy and reduce maintenance or improve comfort. "One of the best examples is ice dams," says Huelman. "Ice damming is totally driven by heat loss. I can fix that problem and save them energy. But that's just a secondary benefit. They're sick and tired of scraping and raking or paying somebody to repair the roof."

NORTHERNSTAR ENERGY EFFICIENT HOUSING RESEARCH PARTNERSHIP TEAM, $400,000

CAPTURING LOST HEAT AS ELECTRICITY

As much as half the energy used by U.S. industry is lost as waste heat. That's why a novel electrical-generating process under investigation by **Richard James,** professor of aerospace engineering and mechanics in the College of Science and Engineering, is so exciting. It might provide a way to capture heat generated by devices from power plants to internal combustion engines to hand-held electronic devices and turn it into electricity.

The process depends on unusual "multiferroic" alloys that suddenly shift from nonmagnetic to strongly magnetic with a slight change in temperature. The change in magnetic state can drive a current in a surrounding coil, recapturing lost energy. "There are no moving parts," says James. "In this sense, the material is the machine." Other technologies change heat to electricity, but the process represented by this new alloy shows promise of producing more power.

In the years ahead, James will try to identify new alloys and learn more about the phase transformations. He will investigate a thin-film application of the alloys for use in computers and other electronics. He also wants to find opportunities for optimizing energy conversion efficiency and power output, while tailoring alloys to different temperature ranges.

"Agencies that could fund this work in a big way need to be educated about this technology," says James, who is conducting his research with a one-year IREE grant. "IREE has jump-started this energy technology at the most critical time."

NEW ENERGY TECHNOLOGY BASED ON THE DIRECT CONVERSION OF HEAT TO ELECTRICITY USING MULTIFERROIC ALLOYS, $70,000

USING SUNLIGHT TO CAPTURE CO_2

Rising levels of atmospheric carbon dioxide from burning fossil fuels is the chief factor driving global climate change.

Imagine a process that would strip CO_2 from the atmosphere to be sequestered (such as deep underground) or processed with water to produce synthetic renewable hydrocarbon fuels. And the whole process would be driven by the renewable energy of sunlight.

That's the tantalizing promise behind the IREE-funded project of **Wojciech Lipinski,** assistant professor of mechanical engineering in the College of Science and Engineering. The key is the capture of CO_2. Lipinski is investigating a two-step thermochemical process to remove CO_2 from the atmosphere or power-plant flue gases in one step and then release the CO_2 for sequestration or for renewable production of gasoline, diesel or kerosene (which would save money by preserving much of our fuel distribution infrastructure and vehicle design).

"The major difference between our research and that of many others is the use of concentrated solar energy, a renewable resource, as the exclusive source of process heat for the cycle rather than fossil fuel combustion," says Lipinski. An IREE grant supports the design, fabrication and testing of the reactor at the University's Solar Energy Laboratory in the College of Science and Engineering.

Lipinski hopes the prototype will become the first step toward industrial use of his CO_2-capture technology. "Similar research activities are being pursued in Europe, most notably at the Swiss Federal Institute of Technology Zurich, where CO_2 capture has attracted the interest of the petroleum industry, and leads to creation of spin-off companies."

SOLAR THERMOCHEMICAL CO_2 CAPTURE, $149,546

CHARGING BIG BATTERIES ON THE MESABI

PUMPED HYDRO ENERGY STORAGE, $250,000

Intermittent power such as wind needs a big "battery"—a way to store energy when it's abundant and provide energy when the wind isn't blowing. One way to do so on a grand scale is using excess energy to pump water from a low elevation to a higher reservoir so it can flow back downhill and drive turbines when the power is needed.

Where to find such huge reservoirs? Minnesota has a unique and largely untapped resource for pumped hydro energy storage—the idled taconite mines on the Mesabi Iron Range.

In an IREE-funded project, **Donald Fosnacht,** director of the Center for Applied Research and Technology Development at the University of Minnesota Duluth, is studying the economic, environmental and social issues of engineering the mine pits as energy storage for a possible wind farm.

Fosnacht is leading a team in studying these issues, including engineers from the St. Anthony Falls Laboratory and the Department of Civil Engineering at UMD, economic and government experts at the Humphrey School of Public Affairs and geologists at UMD.

"IREE has been integral in assembling a diverse team of researchers," says Fosnacht. "The study should result in not only development of the characteristics of sites that may have good potential for future pumped hydro storage, but also the issues that will need to be carefully assessed that will allow this type of concept to be implemented."

HEATING AND COOLING A CAMPUS WITH CORN RESIDUE

Low-value agricultural by-products might provide a feedstock for biofuels, not only substituting for fossil fuels, but also boosting farm income.

Several years ago, with help from IREE, the University of Minnesota West Central Research and Outreach Center built a biomass gasifier to evaluate the use of farm products—principally corncobs, but also waste wood and grasses—to heat and cool the University of Minnesota Morris campus.

"We wanted to know if we could use biomass to replace the energy we were getting from fossil fuels," says **Joel Tallaksen,** scientist with the center. "It's not a huge plant, but it's something we can put in a lot of rural communities around the state."

In the Morris gasifier, biofuels are burned with limited oxygen to generate producer gas, which fuels a furnace more efficiently and cleanly than the biomass itself. The producer gas also becomes an alternative to fossil fuels traditionally used in this application. Furthermore, the purchase, collection and densification of biomass leads to jobs and other economic benefits for the community.

The project team evaluated the feasibility and cost of harvest, collection, storage, transport and combustion. A second study assessed the effect of harvesting biomass on soil fertility. Most recently, IREE has matched funds from the Minnesota Corn Growers Association and the Agricultural Utilization Research Institute to study factors such as price in supplying biomass statewide.

IREE has helped spread the word about the research. Says Tallaksen, "IREE has been there to help organize outreach and involvement of businesses and policy makers."

MORRIS BIOMASS PROJECT
$500,000 / UTILIZATION OF CORN COBS FOR BIOMASS GASIFICATION SYSTEMS, $74,836

NEW PROJECTS

In July 2011, IREE awarded $4.1 million to 20 new renewable energy projects at the University of Minnesota. Search our database at **z.umn.edu/ireeprojects** for details on all IREE projects.

BIOENERGY & BIOPRODUCTS

Biomass torrefaction: understanding greenhouse gas emissions and potential financial opportunities (RS-0028-12) RESEARCH TEAM: Vance Morey (CFANS), Doug Tiffany (CFANS); TOTAL FUNDING: $69,978 This project extends previous work related to biocoal with detailed analysis of greenhouse gas (GHG) emissions of torrefaction.

Developing intermediate wheatgrass for sustainable co-production of fuel and food (RL-0015-12) RESEARCH TEAM: Donald L. Wyse (CFANS), James Anderson (CFANS), David Mulla (CFANS), William Lazarus (CFANS), Craig Sheaffer (CFANS), Baraem Ismail (CFANS), Devin Peterson (CFANS), Tonya Schoenfuss (CFANS), Mirko Bunzel (CFANS); TOTAL FUNDING: $695,000 This project will address the primary limitations to intermediate wheatgrass becoming a food and fuel crop in Minnesota through interdisciplinary research.

Drop-in jet fuel from renewable resources via enzyme catalyst (RS-0038-12) RESEARCH TEAM: John Lipscomb (CBS), Larry Wackett (CSE), Lawrence Que Jr. (CSE), Carrie Wilmot (CBS); TOTAL FUNDING: $70,000 The goal is to study the major hydrocarbon-fuel-producing enzyme being developed by start-up companies to produce diesel fuel and to re-engineer the enzyme to specifically make a "drop-in," or substitute, jet fuel.

Engineering bacterial bioelectrical catalysts (RC-0003-12) RESEARCH TEAM: Jeffrey Gralnick (CSE), Daniel Bond (CSE), Claudia Schmidt-Dannert (CBS); TOTAL FUNDING: $150,000 This project seeks to use electricity to provide the energy to microbes interfaced with electrodes that will build products instead of breaking them down.

Engineering of protein based nano-bioreactors for biofuel production and biocatalysis (RS-0005-12) RESEARCH TEAM: Claudia Schmidt-Dannert (CBS); TOTAL FUNDING: $58,000 This project aims to develop nanoscale bioreactors that can function inside a microbial cell to increase the efficiency of bioproduct production processes and enable production processes in microbial cells that would otherwise be toxic for the cell.

Microbial communities for enhanced biofuel feedstock production (RC-0007-12) RESEARCH TEAM: Brett Barney (CFANS); TOTAL FUNDING: $150,000 This project seeks to combine the unique properties of chemically bonded inorganic binders with regionally sourced and underutilized red pine forest thinnings to develop moisture-, decay-, fire- and mildew-resistant, value-added structural insulated panels (SIPs).

Next-generation microbial systems for bioconversion (RS-0010-12) RESEARCH TEAM: Robert Blanchette (CFANS), Jonathan S. Schilling (CFANS); TOTAL FUNDING: $70,000 The project goal is to identify better fungi for bioprocessing using yield as the guide.

Production of lipids for biofuel production and human nutrition from cold-tolerant yellow-green alga (RS-0039-12) RESEARCH TEAM: Paul Lefebvre (CBS/CFANS), Carolyn Silflow (CFANS), Steven Heilmann (CBS), Miki Hondzo (CSE), Doug Mashek (CFANS); TOTAL FUNDING: $70,000 This interdisciplinary project will take advantage of the unique features of a newly discovered algal species *Xanthophyceae sp.* to develop a robust and efficient system for the production of lipids for biofuels.

CONSERVATION & ENERGY EFFICIENCY

Understanding drivers of whole-household energy conservation in Minnesota using the Twin Cities household ecosystem project (RS-0016-12) RESEARCH TEAM: Lawrence Baker (CFANS), Jay Coggins (CFANS); TOTAL FUNDING: $69,365 This project aims to develop a measure of "energy poverty" that can be used to examine which households might find it most difficult to reduce energy use.

POLICY, ECONOMICS & ECOSYSTEMS

Rethinking how we manage traffic to reduce emissions while maintaining mobility: a new paradigm for traffic management (RS-0035-12) RESEARCH TEAM: Henry Liu (CSE), Saif Benjaafar (CSE), Shuzhong Zhang (CSE); TOTAL FUNDING: $70,000 The goal of this project is to revisit the fundamentals of traffic operations and introduce emission reduction as a traffic management objective.

SOLAR

Concentrated solar energy devices enabled by wavelength selective mirrors (RS-0011-12) RESEARCH TEAM: Jane Davidson (CSE); TOTAL FUNDING: $69,830 This project addresses a timely opportunity and strategic partnership of the University of Minnesota and the 3M Company to develop advanced hybrid photovoltaic thermal solar collectors using a new mirror film technology developed by 3M.

Enhanced exciton harvesting in organic photovoltaic cells using engineered, graded film compositions (RC-0004-12) RESEARCH TEAM: Russell Holmes (CSE); TOTAL FUNDING: $149,034 In this work, OPVs will be constructed with tailored film composition and morphology to study and engineer the photoconversion process and to maximize performance.

High energy density, nanostructured supercapacitors for electrical energy storage (RL-0012-12) RESEARCH TEAM: Phil Buhlmann (CSE), William Smyrl (CSE), Andreas Stein (CSE); TOTAL FUNDING: $695,000 This project will develop supercapacitor systems that combine high power densities with high energy densities for electrical storage systems.

Materials for 1$/W CIGS-based photovoltaics (RL-0003-12) RESEARCH TEAM: Stephen Campbell (CSE), Eray Aydil (CSE), Wayne Gladfelter (CSE); TOTAL FUNDING: $695,000 This project aims to show that $1/watt solar energy could be achieved by the incorporation of several materials that aren't currently used in copper-indium-gallium-selenide (CIGS).

New energy technology based on the direct conversion of heat to electricity using multiferroic alloys (RO-0002-12) RESEARCH TEAM: Richard James (CSE), Paul Strykowski (CSE), Christopher Leighton (CSE), Matteo Cococcioni (CSE); TOTAL FUNDING: $220,000 The goals of this project are to discover, build and evaluate new sustainable energy conversion devices based on phase transformation in multiferroic materials and to advance the sciences underlying this technology.

Solar thermochemical CO_2 capture (RC-0009-12) RESEARCH TEAM: Wojciech Lipinski (CSE); TOTAL FUNDING: $149,546 This project seeks a major advancement of the solar thermochemical CO_2 capture technology via carbonation/calcinations reaction pairs.

WIND, HYDRO & GEOTHERMAL

Design tools for multivariable control of large wind turbines (RL-0010-12) RESEARCH TEAM: Gary Balas (CSE), Peter Seiler (CSE); TOTAL FUNDING: $278,600 The focus of this project is to develop a framework for efficient design of multivariable controllers for large utility-scale turbines.

Development of self-powered wireless sensor for structural health monitoring in wind turbine blades (RS-0029-12) RESEARCH TEAM: Rusen Yang (CSE), Susan Mantell (CSE); TOTAL FUNDING: $68,281 In this project, a novel approach for realizing a self-powered wireless SHM system for wind turbine blades will be investigated.

Distributed ammonia production using wind-generated hydrogen and power (RO-0001-12) RESEARCH TEAM: Alon McCormick (CSE); TOTAL FUNDING: $400,000 This project includes the development of two new technologies for converting wind-generated hydrogen into ammonia, both of which could ultimately result in economic, small-scale rural processes for generating low carbon, renewable ammonia as a fertilizer for on-farm use.

Evaluating wind farm performance under realistic thermal and complex terrain conditions: the first path towards optimization (RC-0005-12) RESEARCH TEAM: Michele Guala (CSE); TOTAL FUNDING: $150,000 This project aims to optimize the location of the wind farm for a set of given sinusoidal perturbations (i.e., small hills with heights similar to the turbines) in the cross-flow direction.

ACRONYMS

CBS: College of Biological Sciences
CDES: College of Design
CFANS: College of Food, Agricultural and Natural Resource Sciences
CLA: College of Liberal Arts
CSE: College of Science and Engineering
CVM: College of Veterinary Medicine
HHH: Humphrey School of Public Affairs
IonE: Institute on the Environment
UMD: University of Minnesota Duluth
UMM: University of Minnesota Morris

CURRENT PORTFOLIO

The following IREE-funded projects were active between July 1, 2010, and June 30, 2011. Search our database at **z.umn.edu/ireeprojects** for details on all IREE projects, both active and closed.

BIOENERGY & BIOPRODUCTS

Adding value to ethanol production byproduct (distillers grain) through production of biochar and bio-oil (RM-0033-10) RESEARCH TEAM: Kurt Spokas (CFANS), Roger Ruan (CFANS), Bob Morrison (CVM); TOTAL FUNDING: $12,000

Biofuels for the farm: new technologies for the production of biofuels in small systems (RL-0004-09) RESEARCH TEAM: Michael Tsapatsis (CSE), Lanny Schmidt (CSE), David Kittelson (CSE), Edward L. Cussler (CSE), Aditya Bhan (CSE), Prodromos Daoutidis (CSE); TOTAL FUNDING: $600,000

Biohydrogen-based biofuel cells: highly efficient and clean electricity generation using mixed wastewater feedstocks (RS-0010-09) RESEARCH TEAM: Jun Zhu (CFANS), Ping Wang (CFANS); TOTAL FUNDING: $70,000

Catalytic gasification of corn residues (RM-0031-10) RESEARCH TEAM: Lanny Schmidt (CSE); TOTAL FUNDING: $10,000

Conversion of waste lignin to liquid fuels and other high value products, a fundamental study exploring two options (RS-0019-11) RESEARCH TEAM: Ulrike Tschirner (CFANS), Shri Ramaswamy (CFANS), Doug Tiffany (CFANS); TOTAL FUNDING: $69,790

Converting solid biomass to hydrocarbon liquid fuels (RL-0032-09) RESEARCH TEAM: Roger Ruan (CFANS), Lanny Schmidt (CSE), Paul Chen (CFANS); TOTAL FUNDING: $250,000

Designer proteins for efficient enzymatic degradation of recalcitrant cellulose (LG-B4s2-2005) RESEARCH TEAM: Claudia Schmidt-Dannert (CBS); TOTAL FUNDING: $122,500

Developing a reaction transport model that couples chemical reactions of mineral dissolution/precipitation with spatial and temporal flow variations in CO_2/brine/rock systems (RM-0018-10) RESEARCH TEAM: Martin Saar (CSE); TOTAL FUNDING: $64,368

Development and commercialization of an integrated biorefinery for processing DDGS into biofuels and value added products (RL-0010-11) RESEARCH TEAM: Pavel Krasutsky (UMD), Doug Tiffany (CFANS); TOTAL FUNDING: $250,000

Development of torrefied wood microchips as an energy-efficient biofuel for pellet stoves and boilers (RS-0010-11) RESEARCH TEAM: Timothy Hagen (UMD), Brian Brashaw (UMD); TOTAL FUNDING: $66,042

Enhanced biogas formation from animal wastes: evaluation of a new technology for increased biogas quality and quantity (RS-0006-09) RESEARCH TEAM: Michael Sadowsky (CFANS), Daniel Bond (CSE); TOTAL FUNDING: $67,716

Engineering of a multi-species fermentation platform for biofuel production (RL-0001-11) RESEARCH TEAM: Claudia Schmidt-Dannert (CBS), Friedrich Srienc (CSE), Yiannis Kaznessis (CSE); TOTAL FUNDING: $472,500

Evaluating wood energy opportunity zones (RM-0003-12) RESEARCH TEAM: Dennis Becker (CFANS); TOTAL FUNDING: $29,460

Exploiting genetic variation in soybean to increase oil (RM-0001-09) RESEARCH TEAM: Sue Gibson (CBS/CFANS), Jane Glazebrook (CFANS), Fumiaki Katagiri (CFANS), James Orf (CFANS); TOTAL FUNDING: $17,500

Gene expression in the cattails *Typha latifolia, Typha angustifolia* and *Typha x glauca* (SO1-2007) RESEARCH TEAM: Nathan Springer (CBS/CFANS); TOTAL FUNDING: $28,000

Global renewable energy leadership fellows (RO-0002-10) RESEARCH TEAM: Jonathan Foley (IonE); TOTAL FUNDING: $497,318

Hydrothermal carbonization of algae and agricultural wastes: synthetic biocoal (RS-0037-09) RESEARCH TEAM: Michael Sadowsky (CFANS), Kenneth Valentas (CSE), Marc Von Keitz (CSE), Steven Heilmann (CBS); TOTAL FUNDING: $70,000

Improving handling characteristics of herbaceous biomass (RM-0004-11) RESEARCH TEAM: Vance Morey (CFANS), Michael Reese (CFANS); TOTAL FUNDING: $25,000

Innovative, diversified agroforestry plantings in support of energy security, environmental quality and local economies (RM-0016-10) RESEARCH TEAM: Dean Current (CFANS), Craig Sheaffer (CFANS), Kenneth Brooks (CFANS), Donald L. Wyse (CFANS), Gregg A. Johnson (CFANS), Joe Magner (CFANS); TOTAL FUNDING: $35,000

Lactic acid fermentation using dairy manure as the sole carbon and nitrogen source (RS-0004-11) RESEARCH TEAM: Jun Zhu (CFANS); TOTAL FUNDING: $47,677

Mass culture of algae for biofuels (M1-2007) RESEARCH TEAM: Roger Ruan (CFANS), Paul Chen (CFANS); TOTAL FUNDING: $446,840

Mimicking fungal biomass decomposition using biphasic biocatalysis (RC-0008-11) RESEARCH TEAM: Jonathan S. Schilling (CFANS), Ping Wang (CFANS), Shona Duncan (CFANS); TOTAL FUNDING: $135,000

Minnesota microorganisms for electrical biocatalysis (RS-0013-09) RESEARCH TEAM: Daniel Bond (CSE), Jeffrey Gralnick (CSE), David Biesboer (CBS), Randall Hicks (UMD); TOTAL FUNDING: $70,000

Pathways toward sustainable bioenergy feedstock production in the Mississippi River Watershed (RM-0002-11) RESEARCH TEAM: Jason Hill (CFANS), Tracy Twine (CFANS); TOTAL FUNDING: $31,914

Performance and emissions of second generation biofuel DME (RL-0024-11) RESEARCH TEAM: David Kittelson (CSE), Steve Taff (CFANS), Win Watts (CSE); TOTAL FUNDING: $531,000

Regulation of cell wall growth and composition in nitrogen-rixing biomass crops in Minnesota: Medicago and related forage crop and woody species (RS-0018-11) RESEARCH TEAM: Kathryn VandenBosch (CBS/CFANS), Stephen Gantt (CFANS), Ulrike Tschirner (CFANS), Mesfin Tesfaye Gebeyaw (CFANS); TOTAL FUNDING: $69,827

Renewable energy and sustainable chemistry across the undergraduate chemistry curriculum (RM-0018-09) RESEARCH TEAM: Ted M. Pappenfus (UMM); TOTAL FUNDING: $22,000

Research turbidostat for algal cultures (RM-0021-10) RESEARCH TEAM: Igor Libourel (CBS/CFANS), Jeffrey Gralnick (CSE), Brett Barney (CFANS), Adrian Hegeman (CFANS), Jerry Cohen (CFANS); TOTAL FUNDING: $25,000

Shewanella as an ideal platform for producinghydrocarbon fuel (RM-0008-10) RESEARCH TEAM: Larry Wackett (CSE), Jeffrey Gralnick (CSE), Aditya Bhan (CSE), Lanny Schmidt (CSE), Marc Von Keitz (CSE); TOTAL FUNDING: $300,000

Strategies for the reduction of carbon dioxide to methanol (RC-0011-11) RESEARCH TEAM: Connie Lu (CSE); TOTAL FUNDING: $135,000

Sustainable forest feedstock for bioenergy production: Enhancing physical and economic availability (RM-0004-09) RESEARCH TEAM: Dennis Becker (CFANS), Dean Current (CFANS), Anthony D'Amato (CFANS), Mike Kilgore (CFANS), Alan Ek (CFANS); TOTAL FUNDING: $44,895

Sustainable polymers: tomorrow's advanced materials (RL-0009-09) RESEARCH TEAM: Marc Hillmyer (CSE), William Tolman (CSE), Frank Bates (CSE), Thomas Hoye (CSE), Steve Kelley (HHH), Chris Macosko (CSE), Steve Severtson (CFANS); TOTAL FUNDING: $800,000

Transforming corn from a commodity crop to a higher energy, multipurpose biofuel crop (RM-0032-10) RESEARCH TEAM: Rex Bernardo (CFANS), Ron Phillips (CFANS), Nathan Springer (CBS), Roger Ruan (CFANS), Doug Tiffany (CFANS); TOTAL FUNDING: $91,200

University of Minnesota Morris: Corn stover densification project (RM-0034-10) RESEARCH TEAM: Lowell Rasmussen (UMM); TOTAL FUNDING: $18,000

Use of transcriptomics to identify lignin-degrading enzymes in fungi (RS-0028-09) RESEARCH TEAM: Stephen Gantt (CBS/CFANS), Simo Sarkanen (CFANS), Kou Xiong (CLA), Bryan Londre (CBS); TOTAL FUNDING: $75,000

Using genomics to increase soybean biodiesel yield (RM-0003-09) RESEARCH TEAM: Sue Gibson (CBS/CFANS), James Orf (CFANS); TOTAL FUNDING: $20,000

CONSERVATION & ENERGY EFFICIENCY

A multi-port DC–DC converter for universal use with renewable energy sources in residential buildings and fuel cell vehicles (LG-C9-2005) RESEARCH TEAM: Ned Mohan (CSE); TOTAL FUNDING: $115,685

A nationwide consortium of universities to revitalize electric power engineering education by state-of-the-art laboratories (RM-0017-10) RESEARCH TEAM: Ned Mohan (CSE), William Robbins (CSE), Bruce Wollenberg (CSE), Paul Imbertson (CSE); TOTAL FUNDING: $155,000

NorthernSTAR Energy Efficient Housing Research Partnership Team (RM-0042-10) RESEARCH TEAM: Patrick Huelman (CFANS); TOTAL FUNDING: $650,000

Solar daylighting project (RM-0003-11) RESEARCH TEAM: John Carmody (CDES); TOTAL FUNDING: $25,000

Universal utility interface for plug-in hybrid electric vehicles with vehicle-to-grid functionality (RS-0025-09) RESEARCH TEAM: Ned Mohan (CSE); TOTAL FUNDING: $70,527

Utilization of corncobs for biomass gasification systems: comprehensive evaluation and demonstration (D1-2009) RESEARCH TEAM: Michael Reese (CFANS), Joel Tallaksen (CFANS), Jeffrey Strock (CFANS), Deborah Allan (CFANS); TOTAL FUNDING: $74,836

POLICY, ECONOMICS & ECOSYSTEMS

Air pollution impacts of conventional and alternative fuels (RL-0026-09) RESEARCH TEAM: Julian Marshall (CSE), Jason Hill (CFANS); TOTAL FUNDING: $599,786

Biofuels as an integral part of sustainable development (RO-0001-11) RESEARCH TEAM: John Sheehan (IonE); TOTAL FUNDING: $141,989

Combining geothermal energy extraction and CO_2 sequestration to produce clean, renewable, carbon-negative electricity (RL-0014-09) RESEARCH TEAM: Martin Saar (CSE), Elizabeth Wilson (HHH), Steve Taff (CFANS), Thomas Kuehn (CSE), William E. Seyfried (CSE), Harvey Thorleifson (CSE), Steven Hauck (UMD); TOTAL FUNDING: $600,000

Economic evaluation of deploying small- to moderate-scale nitrogen fertilizer production plants in Minnesota using wind and grid-based electrical energy sources (RM-0019-11) RESEARCH TEAM: Michael Reese (CFANS); TOTAL FUNDING: $6,611

Life cycle assessment of various petroleum reduction strategies (RO-0002-11) RESEARCH TEAM: Jason Hill (CFANS); TOTAL FUNDING: $50,000

Low carbon fuel standards (M1-2008) RESEARCH TEAM: Steve Taff (CFANS), David Kittelson (CSE), Jeffrey Apland (CFANS), Tim Smith (CFANS); TOTAL FUNDING: $25,000

Measuring the environmental footprint of corn feedstock for a new biobutanol facility in Luverne, MN (RO-0003-11) RESEARCH TEAM: John Sheehan (IonE); TOTAL FUNDING: $19,646

Next-generation biofuels and the ecosystem services they provide: sustainability and the biomass production landscape (RL-0023-11) RESEARCH TEAM: Jason Hill (CFANS), Steve Polasky (CFANS), David Tilman (CBS), Tracy Twine (CFANS); TOTAL FUNDING: $500,000

Spatial modeling and collaborative landscape design to improve nutrient management, agricultural productivity and ecosystem services in the Mississippi River Basin (RM-0040-10) RESEARCH TEAM: Nicholas Jordan (CFANS), Paul Bolstad (CFANS), David Mulla (CFANS); TOTAL FUNDING: $74,937

State climate action planning (RS-0034-09) RESEARCH TEAM: Elizabeth Wilson (HHH); TOTAL FUNDING: $69,100

The unintended climate consequences of North American carbon sequestration from afforestation and reforestation (RC-0010-11) RESEARCH TEAM: Peter Snyder (CFANS); TOTAL FUNDING: $121,361

SOLAR

2010 Solar Vehicle Project (RO-0001-09) RESEARCH TEAM: Jeffrey Hammer (CSE); TOTAL FUNDING: $25,000

Advancements in solar heating and cooling (M6-2008) RESEARCH TEAM: Jane Davidson (CSE), Susan Mantell (CSE); TOTAL FUNDING: $117,220

Converting mining waste rock to passive solar tiles (RS-0017-11) RESEARCH TEAM: Kyle Bartholomew (UMD); TOTAL FUNDING: $50,000

Converting sunlight into electricity with high-efficiency organic solar cells (RL-0006-11) RESEARCH TEAM: Daniel Frisbie (CSE), David Blank (CSE), Marc Hillmyer (CSE), Christopher Douglas (CSE), Russell Holmes (CSE); TOTAL FUNDING: $500,000

Development of a solar Smoleniec/Stirling hybrid thermo-mechanical generator (RS-0014-11) RESEARCH TEAM: Louise Goldberg (CFANS); TOTAL FUNDING: $63,875

EFRI-RESTOR thermochemical routes to efficient and rapid production of solar fuels (RM-0030-10) RESEARCH TEAM: Jane Davidson (CSE), Wojciech Lipinski (CSE); TOTAL FUNDING: $60,000

Evaluation, validation and demonstration of small-scale renewable energy systems for homes and businesses (RL-0007-09) RESEARCH TEAM: Michael Reese (CFANS); TOTAL FUNDING: $304,790

Experimental and theoretical investigations of conducting polymers for solar cells (RS-0011-11) RESEARCH TEAM: Ted M. Pappenfus (UMD); TOTAL FUNDING: $59,546

High-throughput nanofabrication technologies for low-cost plasmonic photovoltaics (RC-0009-11) RESEARCH TEAM: Sang-Hyun Oh (CSE); TOTAL FUNDING: $135,000

Improving organic solar cells with graded interfacial modifications (RC-0016-11) RESEARCH TEAM: Aaron Massari (CSE); TOTAL FUNDING: $135,000

Laterally integrated photovoltaic devices (RL-0019-09) RESEARCH TEAM: Philip Cohen (CSE), Joseph Talghader (CSE), James Leger (CSE), P.P. Ruden (CSE), Emmanuel Enemuoh (UMD); TOTAL FUNDING: $800,000

Materials innovation to enable solar home heating in cold climates (RL-0015-11) RESEARCH TEAM: Susan Mantell (CSE), Marc Hillmyer (CSE), Andreas Stein (CSE), Jane Davidson (CSE); TOTAL FUNDING: $300,000

Molecular design of zinc oxide nanoparticle-dye dyads and triads (RM-0024-10) RESEARCH TEAM: Wayne Gladfelter (CSE), David Blank (CSE), Kent Mann (CSE); TOTAL FUNDING: $25,446

New environmentally benign sulfides for sustainable large-scale photovoltaics (RL-0004-11) RESEARCH TEAM: Eray Aydil (CSE), Stephen Campbell (CSE), Christopher Leighton (CSE) ;TOTAL FUNDING: $500,000

Next generation dye-sensitized solar cells (RS-0009-09) RESEARCH TEAM: David Blank (CSE), Wayne Gladfelter (CSE), Kent Mann (CSE); TOTAL FUNDING: $70,000

Routes to high performance multi junction CIGS-based photovoltaics (M7-2008) RESEARCH TEAM: Stephan Cameron (CBS), Eray Aydil (CSE); TOTAL FUNDING: $160,000

Solar recycling of CO_2 to fuels (RL-0003-11) RESEARCH TEAM: Jane Davidson (CSE), Wojciech Lipinski (CSE), Andreas Stein (CSE), Thomas Chase (CSE); TOTAL FUNDING: $499,997

Thermochemical fuels: solar at night (RL-0001-09) RESEARCH TEAM: Jane Davidson (CSE), David Kittelson (CSE), Jerry Fruin (CFANS), Sean Garrick (CSE), Wojciech Lipinski (CSE), Andreas Stein (CSE); TOTAL FUNDING: $900,086

WIND, HYDRO & GEOTHERMAL

Advanced water power project: improved structure and fabrication of large, high-power KHPS rotors (M5-2008) RESEARCH TEAM: Fotis Sotiropoulos (CSE); TOTAL FUNDING: $120,000

An industry/academe consortium for achieving 20% wind by 2030 through cutting-edge research and workforce training (RM-0002-10) RESEARCH TEAM: Fotis Sotiropoulos (CSE), Gary Balas (CSE), Mos Kaveh (CSE), Ned Mohan (CSE), Roger Arndt (CSE), Kim Stelson (CSE), Susan Mantell (CSE), Henryk Stolarski (CSE); TOTAL FUNDING: $400,000

Development and evaluation of a novel, small pilot-scale non-thermal plasma process for the production of nitrogen fertilizer from wind and other renewable resources (RM-0020-11) RESEARCH TEAM: Michael Reese (CFANS), Roger Ruan (CFANS;) TOTAL FUNDING: $28,800

Development of a high-resolution virtual wind simulator for optimal design of wind energy projects (M4-2008) RESEARCH TEAM: Fotis Sotiropoulos (CSE); TOTAL FUNDING: $180,000

Hydrostatic transmission for wind power generation (RS-0008-09) RESEARCH TEAM: Kim Stelson (CSE); TOTAL FUNDING: $57,406

Improving efficiency of wind turbines by means of model-based flow control (RC-0014-11) RESEARCH TEAM: Mihailo Jovanovic (CSE) TOTAL FUNDING: $134,992

Open accumulator compressed air storage concept for wind power (RS-0027-11) RESEARCH TEAM: Perry Y Li (CSE), Terry W. Simon (CSE); TOTAL FUNDING: $68,817

Pumped hydro energy storage (PHES) using abandoned mine pits on the Mesabi Iron Range of Minnesota (RL-0013-11) RESEARCH TEAM: Donald Fosnacht (UMD), Steven Hauck (UMD), Nathan Johnson (UMD), Elizabeth Wilson (HHH); TOTAL FUNDING: $250,000

Sodium sulfur battery energy storage and its potential to enable further integration of wind (M2A-2008) RESEARCH TEAM: Ned Mohan (CSE); TOTAL FUNDING: $58,285

Sodium sulfur battery energy storage and its potential to enable further integration of wind (M2B-2008) RESEARCH TEAM: William Smyrl (CSE); TOTAL FUNDING: $54,981

CONTACT

IonE Director | JONATHAN FOLEY
jfoley@umn.edu, 612-626-9553

IREE Managing Director | DICK HEMMINGSEN
hemmings@umn.edu, 612-624-7266

IREE Special Projects Director | ROD LARKINS
larki071@umn.edu, 612-624-6055

IREE Science Director | JOHN SHEEHAN
sheeh179@umn.edu, 612-626-1143

IREE Project Coordinator | TRACY FALLON
tfallon@umn.edu, 612-626-1203

INSTITUTE ON THE ENVIRONMENT

UNIVERSITY OF MINNESOTA

Driven to Discover℠

1954 Buford Avenue, Suite 325 St. Paul, MN 55108 612-626-9553 iree@umn.edu

environment.umn.edu/iree

Photos by Josh Kohanek [with the exception of St. Anthony Falls Laboratory courtesy of SAFL/College of Science and Engineering, biomass gasification facility courtesy of Morris Alumni Association, and Joel Tallaksen by David Hansen]