WINTER 2012

C2B2

Colorado Center for Biorefining and Biofuels

FOUR PATHWAYS, ONE GOAL: DEVELOP A DROP-IN BIOFUEL

As director of the National Advanced Biofuels Consortium (NABC), Dr. Tom Foust knows full well that exploring the many potential pathways to biofuels commercialization is a mighty undertaking.

Apparently undaunted by the enormity of the task, Foust and the NABC, an organization spearheaded by Golden's National Renewable Energy Laboratory (NREL) and the Pacific Northwest National Laboratory in Richland, Wash., are making solid progress in evaluating several promising routes for converting lignocelluslosic biomass feedstocks (in this case, corn stover and the harvest residue from loblolly pine) to drop-in biofuels — fuels that can serve as direct replacements for, or supplements to, gasoline, diesel and jet fuels, without any changes to existing fuel distribution networks or engines.

"It's not going to make headlines in the *New York Times*, but we have made significant progress in the first stage of our work," says Foust, alluding to the NABC's first year of research and development activity. "We have actually demonstrated pathways for producing gasoline and diesel from lignocellulosic biomass."

Armed with $35 million from the U.S. Department of Energy and an additional $14.5 million from other partners, the NABC and its 17 members from academia, industry, and the public sector are nearly halfway through a two-stage, three-year project to identify, develop and evaluate six process strategies involving lignocellulosic feedstocks.

Following year-long feasibility studies of each of the six, including environmental, economic, and technical/engineering evaluations, the four processes that Foust and his NABC colleagues "down-selected" for further evaluation through August 2013 include:

1. Fermentation of lignocellulosic sugars (FLS). Led by Amyris, work on this pathway focuses on converting biomass into sugars that can be biologically and chemically converted into a renewable diesel fuel certified by the U.S. Environmental Protection Agency to be blended up to 35% with conventional diesel. The goal is to adapt the Amyris diesel fuel fermentation process to accommodate complex lignocellulosic sugar streams. That produces high-quality diesel fuel or chemicals from a 15-carbon isoprenoid called farnesene. Beside Amyris, partners investigating this pathway include Catchlight Energy, Iowa State University, Washington State University, NREL, Pall Corp., Tesoro, and Argonne National Laboratory.

2. Catalysis of lignocellulosic sugars (CLS). Virent Energy Systems is spearheading exploration of this pathway, with support from many of the partners working on the aforementioned FLS pathway. CLS work entails converting biomass into sugars that can be chemically and catalytically converted into a range of gasoline and diesel fuel components, via a process pioneered by Virent that utilizes a variety of plant sugars and converts them to drop-in gasoline, diesel, and jet fuels and fuel components. This so-called BioForming technology combines Virent's proprietary aqueous-phase reforming technology with catalytic steps similar to petroleum refining. While the technology has proven to work during pilot-scale runs using simple sugar streams from beets, corn syrup, and cane juice, further development is needed to make it economical using cellulosic and mixed sugar streams.

3. Hydrothermal liquefaction (HTL). High carbon yields and desirable biofuel product distribution make the HTL pathway especially promising, according to Foust. The goal here, he explains, is to develop stable bio-oil refinery feedstocks via a strategy that entails processing biomass in liquid-phase media at elevated temperatures of 300°–400°C and at pressures fixed by the vapor pressure of the media. The NABC's work with hydrothermal liquefaction is geared toward developing new reaction media and catalysts that reduce process severity, while also examining ways to increase solids loading. The Pacific Northwest National Laboratory is spearheading the effort, in partnership with Albemarle, Argonne National Laboratory, BP, Catchlight Energy, ISU, Los Alamos National Laboratory, NREL, Pall, Tesoro, and WSU.

4. Hydropyrolysis. The thrust of this effort is to convert biomass into hydrocarbon-rich biocrude oil to use as a petroleum substitute for conventional refinery upgrading. The NABC team is focusing on developing multi-functional catalysts to remove oxygen, while maximizing the carbon efficiency of the process and minimizing hydrogen demand. It is also exploring the use of a reactive gas to cap the reactive intermediates formed in pyrolysis vapor to produce a quality bio-oil for refinery integration, while investigating catalyst formulations in attrition-resistant materials for circulating fluid bed applications analogous to fluid catalytic cracking technology. The RTI-led team is using process modeling to explore a wide range of commercial concepts, with an eye toward integrating this technology into existing refineries or developing stand-alone processing and upgrading facilities. Other team members include Argonne, PNNL, UOP, Albemarle, Pall, NREL, ISU, Catchlight Energy, BP and Tesoro.

Having been identified by the NABC as the most promising pathways, these four processes will soon undergo more thorough evaluation to determine which, if any, warrant moving to the pilot stage. Participants in each of the four projects are currently "doing a lot of behind-the-scenes stuff," with the goal of launching larger-scale (though still relatively modest in volume) laboratory production runs this coming summer and fall, according to Foust.

"It's a very aggressive timeline," he says, noting that work on the two pathways involving lignocellulosic sugars is currently slightly ahead of work on the other two pathways.

Stage 2 work will include more rigorous economic, technical and environmental analyses of each of the four processes. By this spring, Foust expects the teams will choose a single feedstock to use — either corn stover or harvest residue. Improving catalysts will be another area of focus, especially with the hydropyrolysis process, leading up to the integrated production runs that are slated to begin later this year.

After that, he explains, "we anticipate we will be able to identify the technical challenges and areas we need to improve. We should have a good benchmark of where we stand, so we can make final improvements before we contemplate [subjecting the fuels produced by the processes to] engine testing."

Then, if things go according to plan, comes the work of further developing those processes and technologies to pilot-readiness. Once its work is done in August 2013, the NABC is required to deliver to the Energy Department a technology package that includes a pilot plant-ready process, a detailed design and engineering report, and a life-cycle analysis. That, hopefully, will

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Colorado Students in the Spotlight

Aaron Palumbo is a third year Ph.D. candidate in the Chemical and Biological Engineering department at the University of Colorado Boulder. Throughout his undergraduate and graduate career, Aaron has worked on academic projects with industry partners Solix Biofuels, ConocoPhillips, and Sundrop Fuels. During his first year in graduate school he received an NSF AGEP fellowship. Aaron currently studies the complex transport phenomena occurring in a novel thermochemical process for the production of synthesis gas from biomass and natural gas using concentrated solar energy. He hopes his research will add value to the attempts at commercialization of this process. His modeling and experimental efforts will lay a strong foundation for future Ph.D. projects to build upon. After graduation, Aaron plans to continue working on renewable fuels within an industry setting.

FOUR PATHWAYS

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set the stage for ultimately integrating a process into existing refineries and distributions systems to actually bring biomass-derived petroleum alternatives to market. That's when the work of the NABC will truly be vindicated.

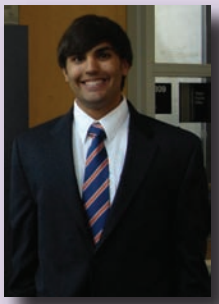
It is important to note that the Colorado School of Mines plays an instrumental role as a partner in the NABC project. Mines researchers work on understanding the underlying chemical and physical mechanisms of biomass conversion to hydrocarbon fuel, contributing to the development of efficient and economical conversion processes. Researchers at Mines recognize the importance of working with C2B2 partners, such as NREL, in these collaborative projects in order to share and develop expertise which often leads to new partnerships and new research opportunities.

For a complete list of partner organizations working with NABC on the drop-in biofuels project, please visit:

www.nabcprojects.org/partners.html

For a Department of Energy news article highlighting this NABC project, please visit:

http://apps1.eere.energy.gov/news/progress_alerts.cfm/pa_id=597



Alex Román, a sophomore in Chemical Engineering specializing in Environmental Engineering at Auburn University in Auburn, AL, was a participant in the C2B2/NSF-REU summer research program in 2011. Alex recently placed 2nd in the American Institute of Chemical Engineering's Student Poster Competition in the Catalysis and Reaction Engineering Division for research he conducted during the C2B2 REU. His work, entitled Surface Chemistry of Unsaturated Biomass Derived Alcohols on a Palladium (111) Catalyst, was conducted with Dr. Will Medlin and investigated the effects that a Palladium catalyst had on various functional groups within an unsaturated alcohol. An application of this research includes the possibility of upgrading alcohols that are found in the byproduct of the thermochemical processing of biomass to bio oil into useable fuels. After completing his Bachelor's degree, Alex plans to pursue a Ph.D. in Chemical Engineering, specifically in catalysis development.

April Corpuz is a fifth year Ph.D. student in the Chemistry Department at Colorado School of Mines. April is a 2009-2011 C2B2 Chevron Graduate Fellowship recipient for her work on making biofuel from "waste" lipids. Her research utilizes (111)-faceted rock salt metal oxides to transesterify methanol and glycerophospholipids to make fatty acid methyl esters. Thanks to the C2B2 Chevron Graduate Fellowship, April was able to travel to Spain and present her work at the 1st International Congress on Catalysis for Biorefineries. After graduation, April plans to continue research at the triple boundary of chemistry, materials science, and renewable technologies.

Mike Griffin is a fourth year Ph.D. candidate in the Chemical and Biological Engineering Department at the University of Colorado Boulder. Mike's research, which has been published in Surface Science and The Journal of Physical Chemistry, contributes to the development of catalytic materials for biorefining applications by providing insight into how multifunctional oxygenates interact with transition metal surfaces. Mike is the recipient of a 2008 University of Colorado Dean's Outstanding Merit Fellowship, is a 2009 Graduate Assistantship in Areas of National Need, and a 2011 C2B2 Seed Grant. He has also served as a mentor in the C2B2 Research Experience for Undergraduates program and the Discovery Learning Apprenticeship program. After graduation Mike hopes to continue his work in the field of biorefining.

C2B2 Semi-Annual Meeting

March 20 - 21, 2012 — University of Colorado Boulder

TUESDAY, MARCH 20, 2012

Noon - 1:30p ..... Luncheon

2 - 4:30p .....Tours
New CU Jennie Smoly Caruthers Biotechnology research facility and local industry facility

5:30p..... Networking Reception

WEDNESDAY, MARCH 21, 2012

7 - 8a ..... Breakfast

7 - 9a .....Business Meeting
Collaborative insight on the future of industry research & challenges

9a ..... Research Presentations

11:30a ..... Meeting Concludes

Please RSVP by March 1, 2012

Questions? Please e-mail: C2B2@colorado.edu or call Frannie Ray-Earle at 303-492-7736

A New Pathway, But Green Gasoline Still Sundrop Fuels' Goal

To survive on the often unpredictable, volatile biofuels frontier, a company has to be ready to reinvent itself on the fly. That's exactly what Longmont, Colo.-based Sundrop Fuels (www.sundropfuels.com) has done in the span of a little more than a year, having overhauled the technological thrust of its advanced biofuels production concept while remaining on course to open its first "green gasoline" refinery by 2014.

As recently as late 2010, Sundrop Fuels, a C2B2 sponsor, envisioned producing biofuel at towering "solar parks" where biomass (such as miscanthus and switch grass) would be gasified into a synthesis gas (syngas) using solar energy gathered by thousands of mirrors, then refined into tank-ready gasoline. Barely a year later, Sundrop Fuels remains focused on commercializing its biomass gasification technology and gasoline refining process, but minus the mirrors. Instead, the company will use natural gas to create the ultra-high temperatures needed to power the biomass gasification. The switch to natural gas a as power source was necessitated by the prohibitively high cost of solar energy equipment, explains Sundrop Fuels' senior vice president Barry Schaps. "It was just way too expensive and not a power source that we could use 24 hours a day, which is what you need for an economically efficient manufacturing facility."

Undaunted, Sundrop Fuels in November 2011 announced plans for its first production facility on a 1,200-acre site in Rapides Parish, La., near the city of Alexandria, where it can access nearby sources of natural gas and woody biomass. The $450-$500 million plant will be funded in large part by a recent cash infusion from equity investor Chesapeake Energy, the nation's second-largest natural gas producer, with additional financing expected to come via the sale of tax-exempt private activity bonds. Besides Chesapeake Energy, two venture capital firms, Oak Investment Partners and Kleiner Perkins Caufield & Buyers, also own stakes in Sundrop Fuels.

Beginning with the Louisiana project, Sundrop Fuels' goal is to produce a "drop-in," or "tank ready," gasoline — one that's fully compatible with today's internal combustion engines and distribution infrastructure— that costs as much or less at the pump than the petroleum-based competition, even without government subsidies. Target annual production for the plant is 50 million gallons, says Schaps. "It will be finished gasoline, not a blend stock."

Slated to open in late 2014, the Rapides Parish biorefinery will rely on two resources produced abundantly in Louisiana: forest timber and natural gas. The first commercial production plant will provide a platform for the field integration of Sundrop Fuels' proprietary RP Reactor™ radiant particle heat transfer gasification technology. The ultra-high-temperature, high-efficiency method gasifies any cellulosic feedstock in combination with hydrogen stripped from natural gas produces a clean, renewable synthesis gas that then is refined into "green gasoline."

The Alexandria, La., plant will have convenient access not only to local natural gas supplies, but also to an abundant nearby supply of woody biomass. "Timber is Louisiana's largest cash crop," says Schaps. "We should be able to source 100% of our total biomass requirement within a 75-mile radius of the plant."

The versatility of the RP Reactor technology makes it promising, particularly in areas where natural gas and wood waste are readily accessible, according to Schaps. "We can use other biomass sources, such as storm debris and industrial debris — really any wood that would normally go to the landfill, we can use at the plant."

All of which has Schaps and Sundrop Fuels looking further into the future. Engineering, construction, and permitting of the first production facility will keep the company occupied for much of the next two years. The company's plans call for a second, 150-million-gallon green gasoline plant, followed by additional facilities combining to a production capacity of more than one billion gallons by 2020. Sundrop Fuels has not yet announced where it will put the second or subsequent biorefineries.

There's a chance some of that production could come in Colorado, whose timber and natural gas resources make it a logical candidate to someday house a Sundrop Fuels green gasoline facility, according to Schaps. Thus, he says, it makes good strategic sense for the company to use its C2B2 sponsorship as a means to connect with other biofuels stakeholders in the state. "C2B2 is proving to be a valuable information source for us, and we want to be a partner in helping the state's biofuels industry grow."

With Dow as a Partner, OPXBIO Finds the Fast Track

When you're a relatively new company relying on an unproven technology to carve out a niche in a still-nascent industry, false starts, delays and dead ends tend to come with the territory. But in an emerging market where timelines seemingly are made to be broken, Boulder-based OPX Biotechnologies is an exception, having managed to meet and even beat targets for developing an industrial-scale process to produce a renewable, biomass-derived chemical it calls BioAcrylic.

Using its proprietary EDGE™ (Efficiency Directed Genome Engineering) technology, OPXBIO (www.opxbio.com) succeeded in reducing the effective cost of its BioAcrylic by more than 85% in just the first six months of an 18-month pilot project that ended in early 2011. During that year-and-a-half, development and testing of the microbe and fermentation process to produce BioAcrylic unfolded "with unprecedented speed and capital efficiency," according to the company, which was founded in 2007 by Dr. Mike Lynch using genetic mapping technology he helped develop in the laboratory at the University of Colorado Boulder.

Lynch and colleague Mike Rosenberg attribute the speed and efficiency at which the company was able to meet project targets largely to EDGE, which allows the engineering of microbes "in a directed way, in a relatively short timeframe," explains Rosenberg.

"It's analogous to a mapping technology," adds Lynch, "where a set of tools allows us to quickly determine which modifications to make to microorganisms to have them do what we want."

Armed with EDGE, OPXBIO, a C2B2 member, is seeking to compete in the large and growing $8 billion global market for acrylic, a chemical traditionally derived from petroleum and used to make products such as diapers, detergents, paints and adhesives.

The pilot project represented a solid step on the path to commercialization. It verified that OPXBIO can produce BioAcrylic at a 25% lower cost, and with

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Contact Information

Colorado Center for Biorefining and Biofuels
University of Colorado Boulder, 523 UCB, Boulder, CO 80309

Frannie Ray-Earle | *Associate Director of Operations & Financial Management*
Melinda Markin | *Newsletter Editor & C2B2 Center Administrator*

Phone: 303.492.7736 | E-mail: C2B2@colorado.edu | website: www.C2B2web.org

C2B2

C2B2 is a research center of the Colorado Renewable Energy Collaboratory
This cooperative research and educational center is devoted to the conversion of biomass to fuels and other products, supported by state, institutional, and industry funds. The mission of C2B2 is to become the world's leading center in biorefining and biofuels research and education.

C2B2 provides private industry with one-stop access to researchers, laboratories, students, and educators from four innovative institutions, each having unique strengths in biofuel and biorefining application areas.

The Colorado Renewable Energy Collaboratory was created to develop energy technologies for rapid commercialization. The Collaboratory consists of the following institutions:

University of Colorado Boulder
Ranked in the top 25 nationally in Chemical and Biological Engineering, Molecular and Cellular Biology, and Biochemistry.

Colorado State University
Ranked in the top 10 nationally in Agricultural Sciences with an internationally renowned Engines and Energy Conversion Laboratory.

Colorado School of Mines
One of the few universities uniquely focused on energy research.

National Renewable Energy Laboratory
The only national laboratory dedicated to renewable energy and energy efficiency research and development (R&D).

SPONSOR SPOTLIGHT

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a 75% reduction in greenhouse gas emissions, relative to petroleum-based acrylic. During the pilot project, OPXBIO achieved a commercial-scale manufacturing cost of 70 cents per pound for BioAcrylic using corn sugar feedstock and 55 cents per pound using cane sugar feedstock, with a 79% production yield.

Those kinds of results will get a company noticed. In Spring 2011, OPXBIO forged a joint development agreement with Dow Chemical to scale up and commercialize the technology for producing BioAcrylic. One of the chief goals of the project, according to Rosenberg, is to demonstrate that the microbe and fermentation process can work as efficiently on a large commercial scale (in a 50,000-100,000 liter fermenter) as they have in the lab. The partners are aiming to produce a drop-in, biomass-derived acrylic at a cost less than petroleum-based acrylic, using corn sugar as the primary feedstock.

Nine months into what's envisioned as a three-year project, the scale-up process "is going along very well," Rosenberg says.

"If we succeed [with the demonstration project] during the next two years, commercialization will follow around the 2015-2016 timeframe," he adds, noting that OPXBIO and DOW "would like to commercialize [BioAcrylic] together."

Fortified by a recent infusion of $41.2 million in private equity financing from a range of new and existing investors, OPXBIO is pursuing development of a second biomass-derived product, diesel fuel, produced using EDGE technology in tandem with a fermentation process involving carbon dioxide and hydrogen.

OPXBIO is about half way through a development project funded by the U.S. Dept. of Energy's Advanced Research Projects Agency – Energy (ARPA-E) that began in 2010. The goal is to produce a microbial biodiesel equivalent fuel for $2.50 per gallon or less, with the ability to convert that fuel into other fuel molecules such as jet fuel via a catalytic process. So far, so good, says Lynch. "We're on target to meet our milestones and we should be able to start piloting within a year-and-a-half."

Continued progress could ultimately result in a partnership similar to the one forged with Dow, according to Rosenberg. "One of our strategies as a company is to joint venture if possible, since these types of projects tend to be so capital-intensive."