NATIONAL RENEWABLE ENERGY LABORATORY





Bioenergy Research at NREL

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Wednesday, June 8, 2016

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 History

- NREL began operations in 1977 as SERI
- Elevated to national laboratory status in 1991
- NREL is one of 12 DOE national laboratories in United States
- Only national laboratory dedicated to renewable energy and energy efficiency R&D





NREL Today- 40 Years of Clean Energy Research

- World class facilities and renowned scientists
- Nearly 1,700 people
- Collaboration with industry and university
- Market relevant research
- Wide array of programs
- National annual economic impact of $872M

Bioenergy Vision

OUR VISION

To develop bioenergy technologies *that transform the marketplace*

NREL has 30+ years of experience in support of the biofuels industry

Bioenergy Value Chain and NREL's Role

Feedstock Supply and Logistics	Conversion * Technology Development	Integrated Biorefinery Deployment	Infrastructure * and End-Use	Economic and Sustainability Analysis
Developing commodity-scale feedstock supply and logistics systems	Improving conversion efficiencies, yields, and costs; demonstrating process integration	Systematically validating and deploying technology at first-of-a-kind facilities	Evaluating vehicle emissions, performance, and deployment options	Developing approaches to sustainability and providing public economic analyses

* *Major NREL Roles*

Providing Solutions with **Experience** and Scalability

Bioenergy Feedstocks

30+ YEARS OF EXPERIENCE WITH DIVERSE FEEDSTOCKS

- Screening
- Bulk Handling
- Sampling
- Densification

Feedstock Deconstruction

LAB SCALE → PILOT SCALE

- Screening
- Pretreatment
- Deacetylation
- Mechanical Refining

Bioprocess Development

LAB SCALE → PILOT SCALE

- Screening
- Enzymatic Hydrolysis
- Fermentation

Bioproducts

SUGAR

FUELS

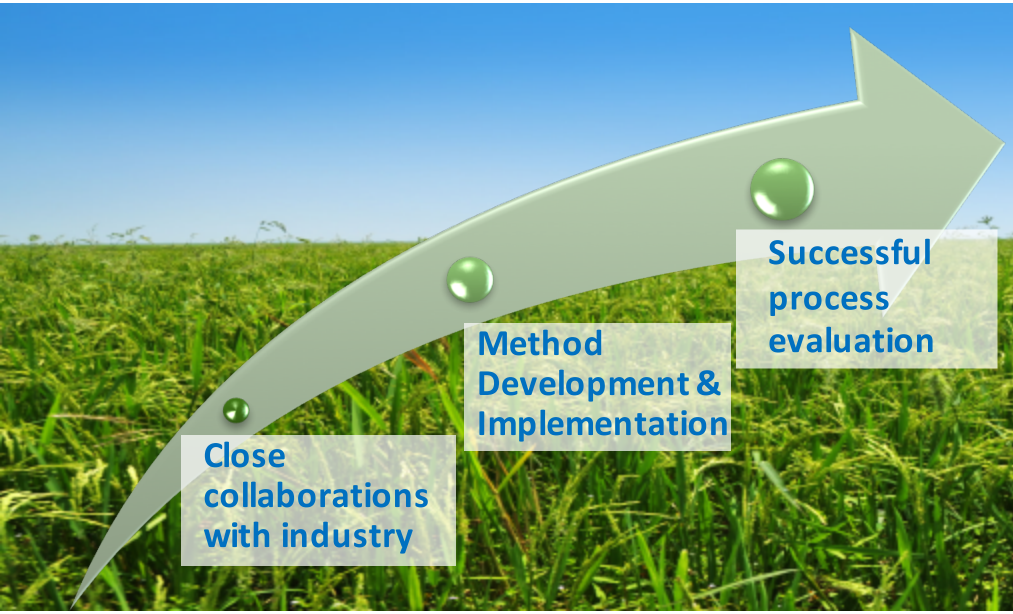
CHEMICALS & PRODUCTS

INTEGRATION ACROSS PROCESS

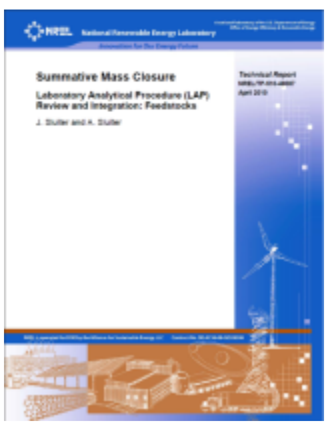
ANALYTICAL

- Compositional Analysis
- On-Line and At-Line Characterization
- Techno-Economic Analysis

Analytical Characterization



- **<u>Why is good data important?</u>**
- Allows you to <u>understand</u> a process
- Understanding lets us <u>optimize</u>
- Optimization generates <u>maximum profit</u> and best use of materials

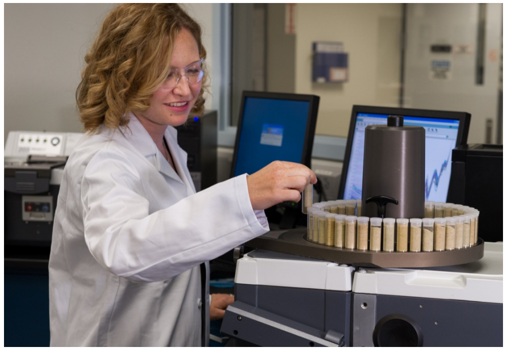


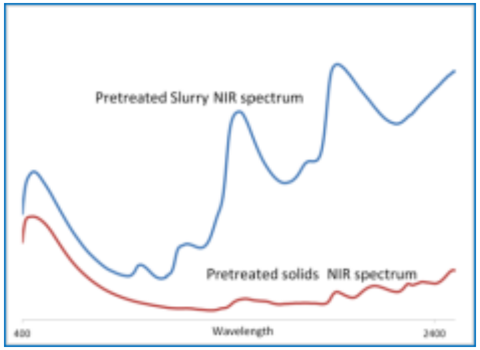
Laboratory Analytical Procedures (LAPs)

- *De facto* standards for biofuels industry worldwide
- Detailed constituent analysis
- Adopted by ASTM
- Everyone speaks the same "language"
- Newly revamped website
- Free download for community resource

Internationally recognized biofuels procedures

Near Infrared (NIR) Calibration Models for Rapid Compositional Analysis





NIR provides chemical composition in seconds by correlating NIR spectra with constituent chemistry

NIR Advantages

- Hundreds of samples analyzed per day
- Bulk sample analysis
- At-line and on-line scanning
- Minimal sample preparation
- Minimal operator experience

We work with many external partners, based on our reputation for excellence in cellulosic compositional analysis

Models available for licensing

- ❖ Corn stover feedstock
- ❖ Mixed herbaceous feedstock
- ❖ Sorghum feedstock
- ❖ Process Intermediates
- ❖ Total Sugar Yield

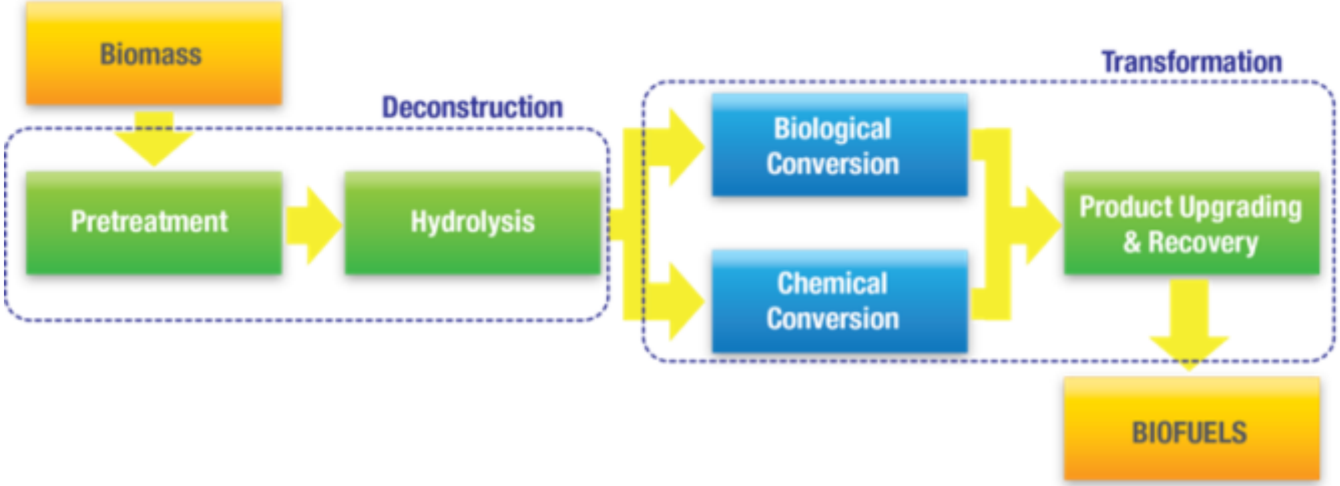
Tiered agreement system

- ❖ Spectra & constituent chemistry
- ❖ Model installation
- ❖ Custom model creation

Feedstock Deconstruction

Deconstruction

- Biomass is usually pre-treated to make it amenable to hydrolysis
- Pretreatment can be a combination of chemicals, heat, or physical deconstruction
- Pretreatment options
    - Deacetylation with caustic solution
    - Dilute acid
    - Mechanical refining
- Mixed feedstocks



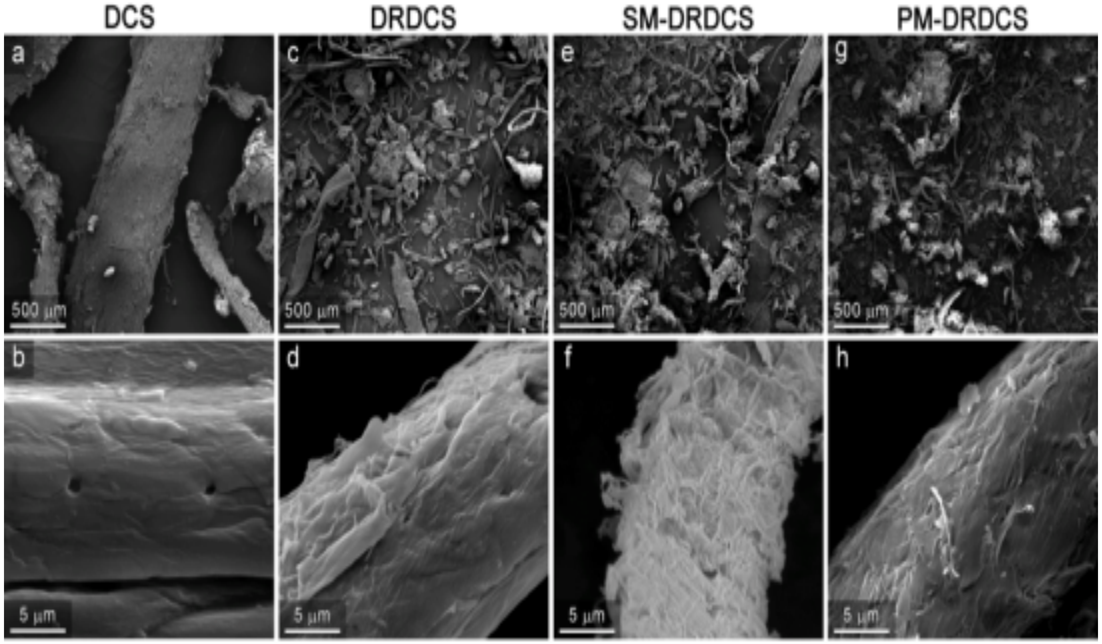
Integration and Scale-Up

- Ability to develop, validate, and integrate a wide variety of biochemical conversion processes
- Scale relevant to industry- 1 ton/day pilot plant
- Extensive pretreatment, enzymatic hydrolysis, fermentation, and product recovery capabilities
- Experienced process engineers and world-class scientists

DUPONT AMYRIS VIRENT Cobalt International Energy ecopetrol

Deacetylation and Mechanical Refining

- Deacetylation and mechanical refining (DMR) is a chemical and mechanical conversion process
- DMR provides *low toxicity, high concentration sugar streams*
- SEM imaging revealed that DMR caused significant surface disruption of the biomass, *providing better sugar accessibility*



Chen X, et al., "Improving Sugar Yields and Reducing Enzyme Loadings in the Deacetylation and Mechanical Refining (DMR) Process through Multistage Disk and Szego Refining and Corresponding Techno-Economic Analysis". ACS Sustain Chem Eng, 4, 324–33 (2016)

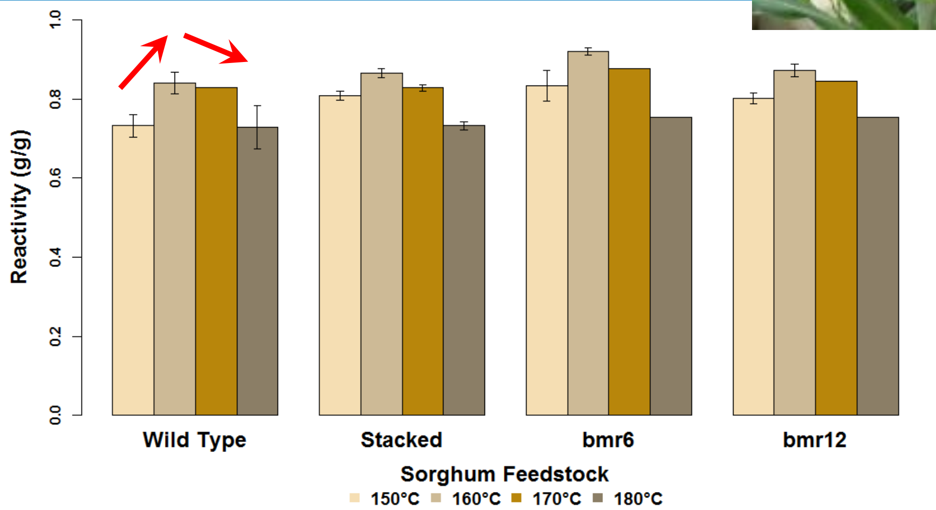
Laboratory-Scale PT/EH Screening

PRETREATMENT

ENZYMATIC HYDROLYSIS

Highlights

- Pretreatment followed by enzymatic hydrolysis
- High throughput with small sample volume
- Small scale allows for screening
- Consistent pretreatment conditions
- Yields improved for mutants vs wild type
- Temperature affects yield



Forage Sorghum feedstocks (RTx430)
- Wild Type (no mutation)
- bmr6 & bmr12 mutants

Dilute Acid Pretreatment (DA)
- 10% solids loading
- 1.0% H_2SO_4

Enzymatic hydrolysis
- 10% solids loading
- CTec2 cellulase

Wolfrum et al., 38th Symposium on Biotechnologies for Fuels & Chemicals, Baltimore MD, April 2016

New NIR Models for Biomass Composition & Reactivity Characterization

Rapid Analysis of composition and sugar accessibility in biomass feedstocks with near-infrared spectroscopy

Goal is to obtain rapid, accurate chemical composition and sugar accessibility information for biomass feedstocks for the commercialization of biofuels

Model includes:
- Corn stover
- Perennial cool season grasses
- Sorghum
- Switchgrass
- Rice straw
- Miscanthus

Model highlights
- Includes over 200 samples
- Predicts composition (glucan, xylan, lignin, and ash)
- Predicts sugar accessibility
- Will be useful for rapid screening to identify unusual samples

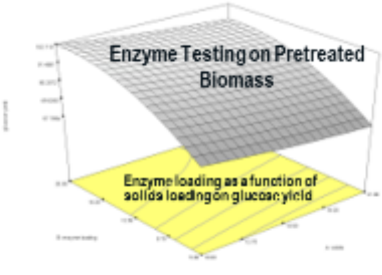
Payne, Courtney E., and Edward J. Wolfrum, "Rapid analysis of composition and reactivity in cellulosic biomass feedstocks with near-infrared spectroscopy," *Biotechnology for Biofuels*, 8, no. 43 (2015). http://dx.doi.org/10.1186/s13068-015-0222-2

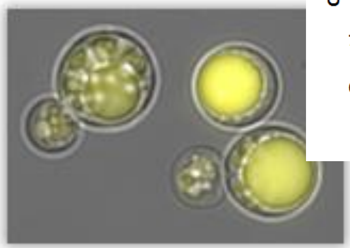
Bioprocess Development- Advanced Fermentation Laboratory

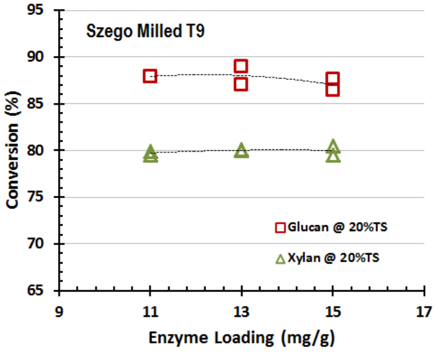
Fermentation

- 36 x 500mL fermentors
- 4 x 5L fermentors
- Batch, fed-batch and continuous flow
- Aerobic, anaerobic, and micro-aerophilic capabilities

- Integration of enzymes and organisms into process streams
- Yield, productivity, and sugar utilization measures
- Molecule specific organism development
- Enzyme and organism performance metrics





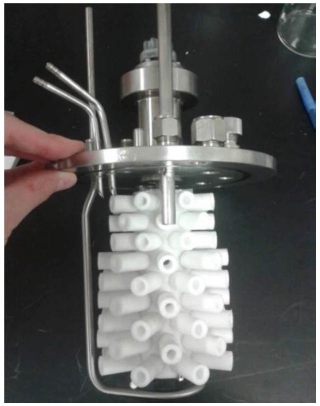


Laboratory scale

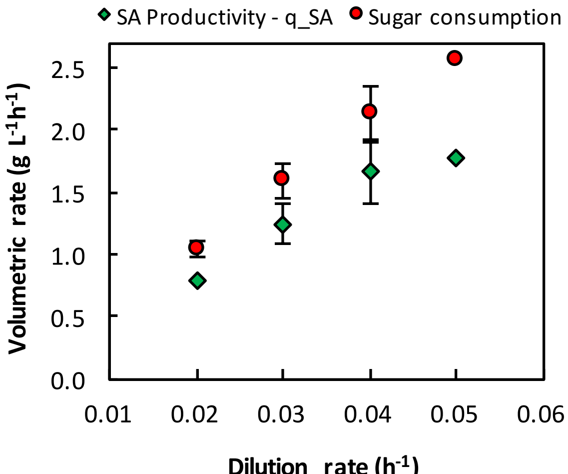
Scalability

170L paddle reactor for enzymatic hydrolysis

Continuous biofilm fermentation producing succinic acid on biomass sugars



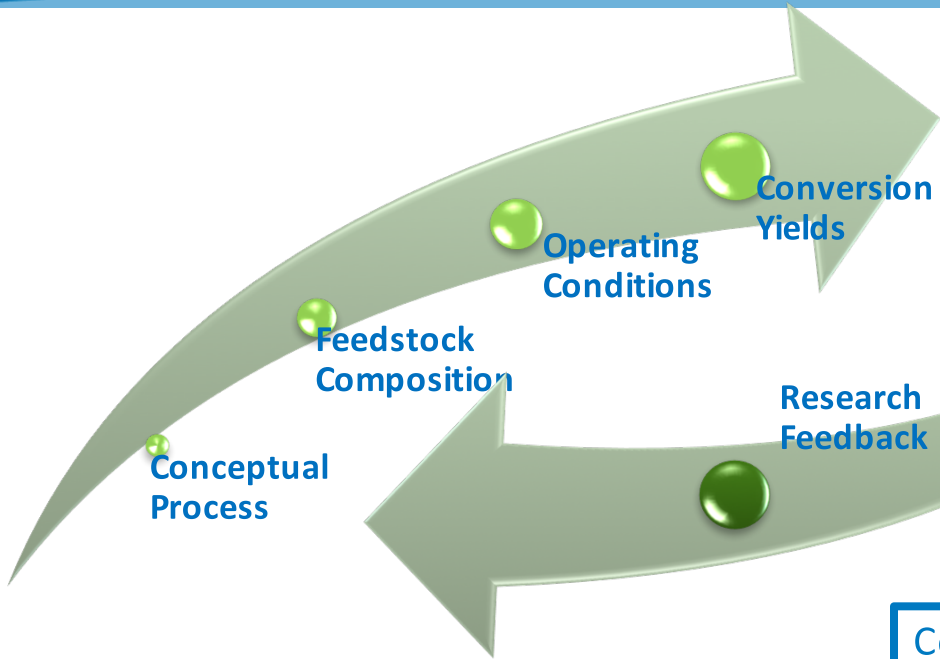
Modified agitator fabricated in-house



	FY14 C5 Liquor – Deacetylated PCS	FY15 C5 Liquor – Deacetylated PCS	2015 Target
Succinic Acid volumetric productivity (g/L-hr)	0.30 (batch culture)	1.4 (continuous culture)	1.0
Process yield (total sugar-to-product, g/g)	0.59	0.62	0.60
Succinic Acid Concentration (g/L)	43.4	43.3	

Bradfield, et al., "Continuous succinic acid production by Actinobacillus succinogenes on xylose-enriched hydrolysate". Biotech for Biofuels, 8:181 (2015)

Techno-Economic Analysis and Life Cycle Assessment



TEA Process Model

- Key Metrics
- MFSP Minimum fuel selling price

Collaboration with engineering and construction firms to enhance credibility and quality

Techno-Economic Analysis (TEA) & Life Cycle Assessment (LCA)

TEA: Assess technical & economic feasibility of process

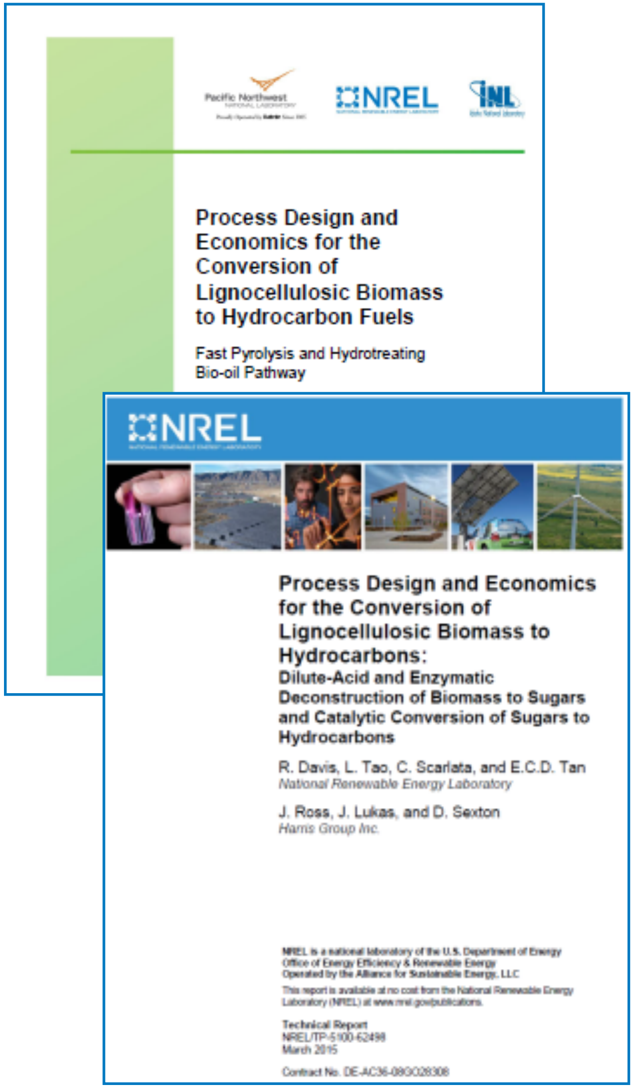
- Modeling is rigorous and detailed with transparent assumptions
- Impact of major cost drivers (sensitivity studies)
- Set research targets & use them as measure of research progress

LCA: Overall environmental impacts of the technology

- Quantification of impacts and areas of improvement

Track research progress (economic & sustainability criteria)

Recent TEA Design Reports (Hydrocarbons Focus)


Pacific Northwest NATIONAL LABORATORY
NREL NATIONAL RENEWABLE ENERGY LABORATORY
INL Idaho National Laboratory

Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels

Fast Pyrolysis and Hydrotreating Bio-oil Pathway

NREL NATIONAL RENEWABLE ENERGY LABORATORY

Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons:
Dilute-Acid and Enzymatic Deconstruction of Biomass to Sugars and Catalytic Conversion of Sugars to Hydrocarbons

R. Davis, L. Tao, C. Scarlata, and E.C.D. Tan
National Renewable Energy Laboratory

J. Ross, J. Lukas, and D. Sexton
Harris Group Inc.

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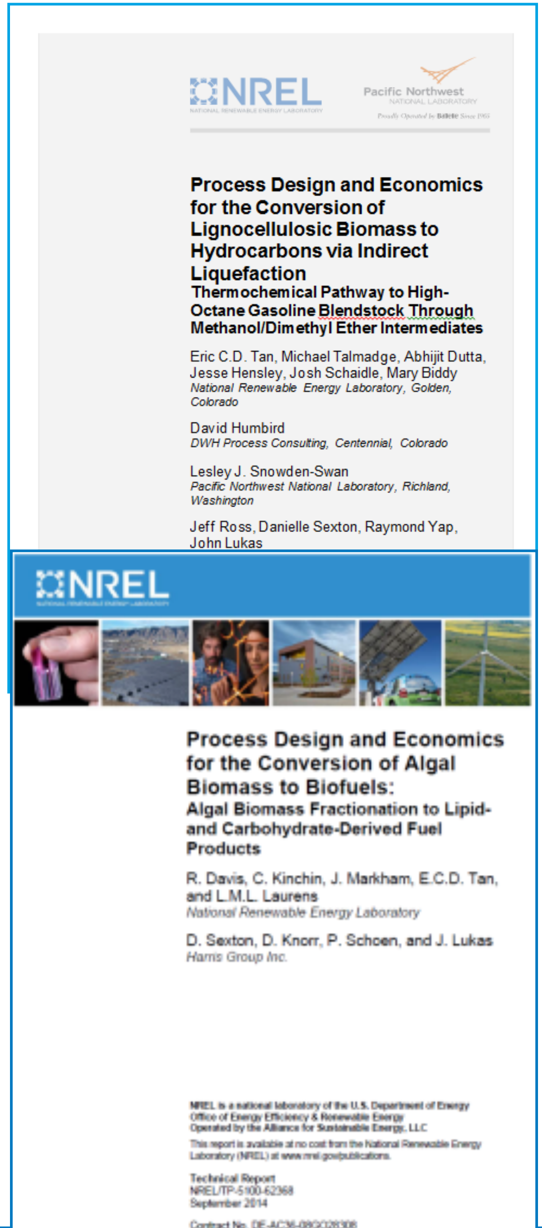
Technical Report
NREL/TP-5100-62498
March 2015

Contract No. DE-AC36-08GO28308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Pacific Northwest NATIONAL LABORATORY

Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons via Indirect Liquefaction
Thermochemical Pathway to High-Octane Gasoline Blendstock Through Methanol/Dimethyl Ether Intermediates

Eric C.D. Tan, Michael Talmadge, Abhijit Dutta, Jesse Hensley, Josh Schaidle, Mary Biddy
National Renewable Energy Laboratory, Golden, Colorado

David Humbird
DWH Process Consulting, Centennial, Colorado

Lesley J. Snowden-Swan
Pacific Northwest National Laboratory, Richland, Washington

Jeff Ross, Danielle Sexton, Raymond Yap, John Lukas

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Process Design and Economics for the Conversion of Algal Biomass to Biofuels:
Algal Biomass Fractionation to Lipid- and Carbohydrate-Derived Fuel Products

R. Davis, C. Kinchin, J. Markham, E.C.D. Tan, and L.M.L. Laurens
National Renewable Energy Laboratory

D. Sexton, D. Knorr, P. Schoen, and J. Lukas
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September 2014

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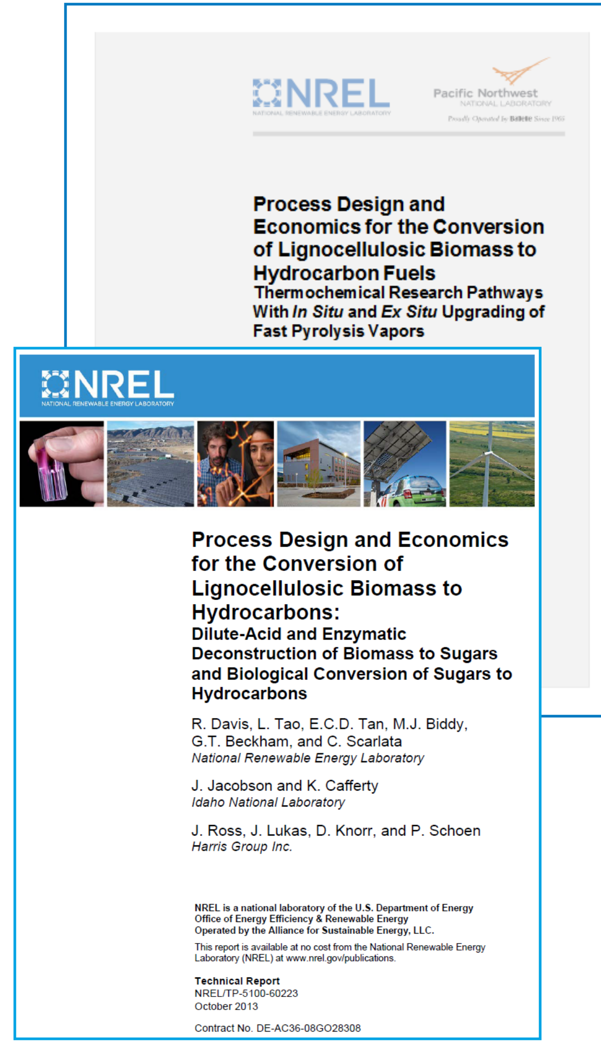
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Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels
Thermochemical Research Pathways With *In Situ* and *Ex Situ* Upgrading of Fast Pyrolysis Vapors

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Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons:
Dilute-Acid and Enzymatic Deconstruction of Biomass to Sugars and Biological Conversion of Sugars to Hydrocarbons

R. Davis, L. Tao, E.C.D. Tan, M.J. Biddy, G.T. Beckham, and C. Scarlata
National Renewable Energy Laboratory

J. Jacobson and K. Cafferty
Idaho National Laboratory

J. Ross, J. Lukas, D. Knorr, and P. Schoen
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October 2013

Contract No. DE-AC36-08GO28308

Pathways Including Thermochemical, Biochemical, and Algal Feedstock Conversion (developed jointly with PNNL)

Co-products are important

Products

Biomass Stream

- Clean sugars
- C5 and C6
- Lignin stream
- Free sugar separation

Transformation

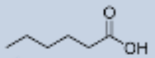
- Organisms, like yeast and E. Coli
- Chemical catalysis

intermediates

- Lipids
- Hexanoic acid
- Muconic acid from lignin
- Succinic acid

Products

- Fuels
- Materials
- Plastics
- Chemicals



NREL Bioenergy Partnerships

Biofuel/Chemical Producers

- Shell
- AMYRIS BIOTECHNOLOGIES
- TESORO
- LanzaTech capturing carbon. fueling growth.
- Chevron Human Energy
- IOGEN CORPORATION
- bp
- Enerkem Creating the Carbon Revolution
- VIRENT
- POET
- ConocoPhillips
- opxbio good chemistry.
- ADM
- ABENGOA
- Cobalt Biofuels
- ecopetrol

Technology Developers & Providers

- GENENCOR A Danisco Division
- CODEXIS
- JM Johnson Matthey
- RTI INTERNATIONAL turning knowledge into practice
- ALBEMARLE
- DUPONT
- novozymes Rethink Tomorrow
- ceres the energy crop company
- HONDA Honda R&D Americas, Inc.
- DOW
- DSM BRIGHT SCIENCE. BRIGHTER LIVING.
- edenspace
- Catchlight Energy A Chevron | Weyerhaeuser Joint Venture
- UOP A Honeywell Company
- BAYER
- PALL Pall Corporation
- ArborGen

Summary

- **Broad focus on feedstocks, deconstruction, and development**
- **Key point is integration across the entire process**
- **Recent Activities**
  - **New NIR Models for Biomass Composition & Reactivity Characterization**
  - **Laboratory-Scale PT/EH Assay**
  - **Deacetylation and Mechanical Refining Process (DMR)**
  - **Continuous biofilm fermentation producing succinic acid on biomass sugars**
  - **Recent TEA Design Reports (Hydrocarbons Focus)**