U.S. DEPARTMENT OF
ENERGY
Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Biochemical Conversion / Lignin Utilization – Day 2

Beau Hoffman, Lisa Guay

Housekeeping

Format:

- Each presentation is 20 minutes
  + 5 minutes of panel Q&A
  + 5 minutes of audience Q&A

- Ryan Lawrence will be giving time checks
  (10 min, 5 min, 1 min remaining)

- Please do not take photos
  (ALL presentations will be posted publicly)

Peer Review Agenda – Day 2

DAY 5 – Friday, April 7, 2023					
8:00 AM	*8:30 AM*	*30*	*Registration, Breakfast*	*All*	
8:30 AM	8:45 AM	15	Technology Area Daily Intro	BETO	
8:45 AM	9:15 AM	30	Continuous Enzymatic Hydrolysis Development	NREL	Mike Himmel
9:15 AM	9:45 AM	30	Production of Low-Cost and Highly Fermentable Sugar from Corn Stover via Chemical-Recovery-Free Deacetylation and Mechanical Refining (CRF-DMR) Process	NREL	Xiaowen Chen
9:45 AM	10:15 AM	30	Sugar is the New Crude	AVAPCO LLC	Kim Nelson
10:15 AM	*10:30 AM*	*15*	*Break*	*All*	
10:30 AM	11:00 AM	30	Biological Upgrading of Sugars	NREL	Jeffrey Linger
11:00 AM	11:30 AM	30	Bench Scale Research and Development	NREL	Nancy Dowe
11:30 AM	12:00 PM	30	Cell Free & Immobilization Technologies (CFIT) to Produce Sustainable Aviation Fuels and Other Bioproducts	NREL	Yannick Bomble
12:00 PM	*1:00 PM*	*60*	*Lunch*	*All*	
1:00 PM	1:30 PM	30	Towards Economical Cell-free Isobutanol Production and Cell-Free Production of Terpenoid Chemical Astaxanthin Using Crude Cofactor Lysates	Invizyne Technologies, Inc	Paul Opgenorth
1:30 PM	2:00 PM	30	Engineered reversal of the β-oxidation cycle in clostridia for the synthesis of fuels and chemicals	Lanzatech (on behalf of Northwestern University)	Shivani Garg
2:00 PM	2:30 PM	30	Fermentative production of Tulipalin A: a next-generation, sustainable monomer that drastically improves the Performance of pMMA	Arzeda	Alex Zanghellini
2:30 PM			*Adjourn*		

Clean / Convertible Sugars

Advanced Fermentations

Next Generation Bioprocessing

BETO’s Strategy for Today’s Presentations

Convertible Clean Sugars

Area Goal: Demonstrate sugars with:

- >90% convertibility (titer/rate/yield) relative to dextrose (as demonstrated by multiple partners)…
- At a cost of <$0.20/lb…
- From multiple sustainable feedstocks…
- While quantifying sustainability impacts

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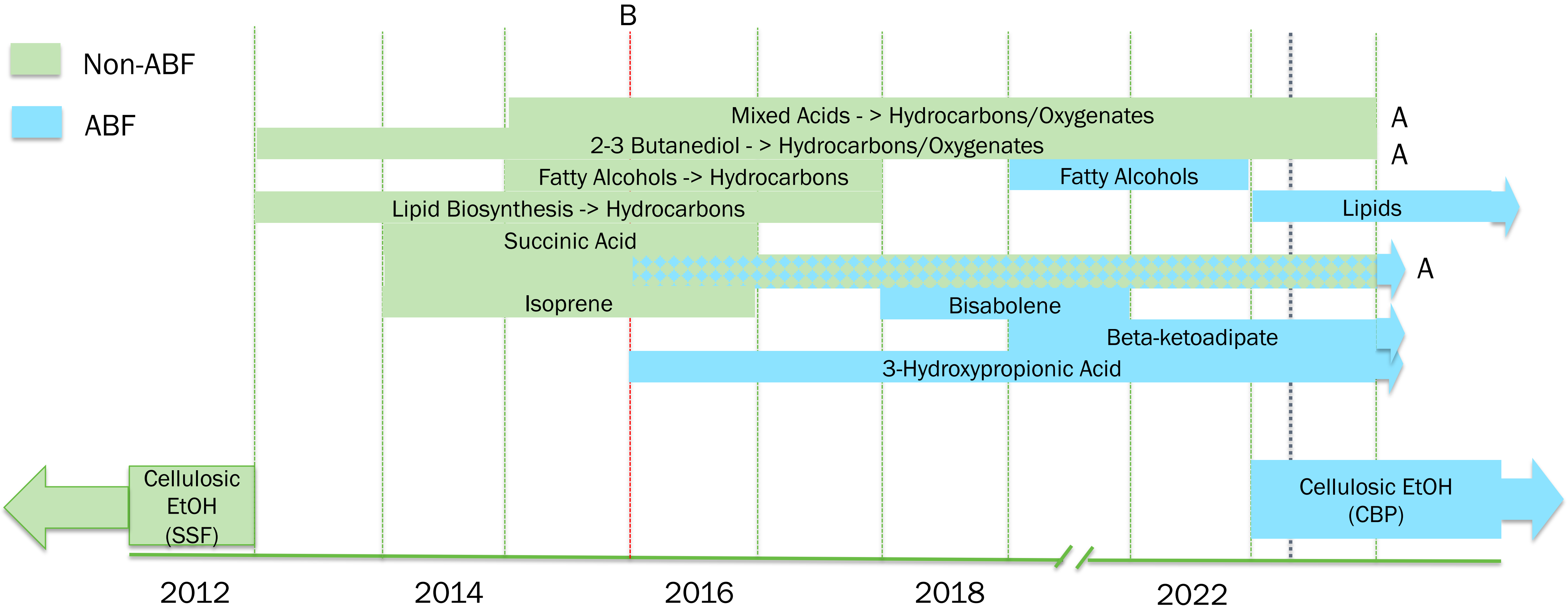
8:45 AM	9:15 AM	30	2.4.1.101	Continuous Enzymatic Hydrolysis Development	NREL
9:15 AM	9:45 AM	30	2.2.3.200	Production of Low-Cost and Highly Fermentable Sugar from Corn Stover via Chemical-Recovery-Free Deacetylation and Mechanical Refining (CRF-DMR) Process	NREL
9:45 AM	10:15 AM	30	2.4.3.201	Sugar is the New Crude	AVAPCO LLC

Biochemical Pathways Through the Years



10:30 AM	11:00 AM	30	2.3.2.105	Biological Upgrading of Sugars	NREL
11:00 AM	11:30 AM	30	2.4.1.100	Bench Scale Research and Development	NREL

A: Undergoing merit review
B: Agile Biofoundry (ABF) Starts

Next Generation Bioconversion

Area Goal: Move beyond proof of principle for the following:

- Achieving co-factor recycling/re-use
- Cell-free 'prototyping'
- Immobilization/stabilization of enzymes

11:30 AM	12:00 PM	30	2.5.4.101	Cell Free & Immobilization Technologies (CFIT) to Produce Sustainable Aviation Fuels and Other Bioproducts	NREL
12:00 PM	*1:00 PM*	*60*		*Lunch*	*All*
1:00 PM	1:30 PM	30	2.5.6.203	Towards Economical Cell-free Isobutanol Production and Cell-Free Production of Terpenoid Chemical Astaxanthin Using Crude Cofactor Lysates	Invizyne Technologies, Inc
1:30 PM	2:00 PM	30	2.5.3.206	Engineered reversal of the β-oxidation cycle in clostridia for the synthesis of fuels and chemicals	Lanzatech (on behalf of Northwestern University)
2:00 PM	2:30 PM	30	2.3.4.208	Fermentative production of Tulipalin A: a next-generation, sustainable monomer that drastically improves the Performance of pMMA	Arzeda

Relevant FOAS / Funding Opportunities

FOA	Opportunities	Targets	Awardees
Clean Sugars FOA	• Clean Cellulosic Sugars (FY21)	<$0.20/lb >90% convertibility demonstrated with at least 3 downstream technologies	NREL AVAPCO
Advanced Bioprocessing	• Advanced Bioprocessing FOA (FY19)	Demonstrate cell free production >0.5 g/L/hr for >72 hours	Invizyne
Other FOAs	• Performance Advantaged Bioproducts (FY18) • USDA BRDI	>10% increase in bioproduct performance*	Arzeda Northwestern U

*Relative to an appropriate benchmark technology
**Not presenting today

Recent Successes Emerging from Biochemical Conversion & Lignin Utilization Work

Genomatica and Renewable Polymers

Conversion Investments:

- 2011-2016: BC FOA supports strain development ($5M)
- 2017-2019: Support for fermentation development and modeling in BSRD Project at NREL (~$100k/yr)
- 2021: Subrecipient of AVAPCO Clean Sugars project

Unilever and Geno launch $120m venture to scale alternative ingredients

BIOPOLYMERS

Published 8/17/2022 | 2 MINUTE READ

Genomatica and Aquafil Start Pre-Commercial Plant-Based Nylon 6 Production

Quantities available for evaluation in nylon applications ranging from yarns for textile and carpet to engineering thermoplastics.

lululemon partners with Genomatica on plant-based nylon

Forbes

In Latest Win For The Bio-Economy, Genomatica Raises $118 Million Led By Novo Holdings

Iowa breaks ground on first U.S. plant producing bio-BDO

May 17, 2022 / Agriculture, Biomanufacturing, State Policy / By Bio.News Staff

New joint venture unveils QIRA, a bio-based 1,4-butanediol (BDO) that saves up to 93 percent of greenhouse gas emissions compared to the use of conventional BDO

Fossil BDO: 4.4 $kgCO_2e/kg$

Bio-BDO:0.3 $kgCO_2e/kg$

This plant alone will result in annual emissions savings of >400,000 T CO_2e/yr

1,4 BDO

(2 million tons/yr)

- Spandex/Lycra
- PBT
- 11% Polyurethane
- GBL
- THF

https://bioplasticsnews.com/bio-bdo-bio-butanediol-novamont/

NREL – Bioprincipia Partnership

Commercialization:

- NREL has developed two collaborations with industrial entities for the Technology Commercialization.

Commercializing Bio-butyric acid derivatives for <u>SAF & chemicals</u>

Company X

Commercializing Bio-butyric acid derivatives for <u>human health</u>

- Intellectual property has been licensed to both entities.
- One Cooperative Research & Development Agreement (CRADA) has been executed and another is currently being negotiated.

Corn Kernel Fiber Analytical Method Development

United States Environmental Protection Agency

Renewable Fuel Standard Program

Guidance on Qualifying an Analytical Method for Determining the Cellulosic Converted Fraction of Corn Kernel Fiber

This updated 2022 guidance benefits from recent scientific advancements, including work conducted by the Department of Energy's (DOE) National Renewable Energy Laboratory (NREL), to develop a public method that addresses the analytical concerns identified in the 2019 guidance.

Ethanol PRODUCER MAGAZINE

EPA updates guidance on corn kernel fiber ethanol production

By Erin Voegele | September 29, 2022

National Institute of Standards and Technology
U.S. Department of Commerce

NREL NATIONAL RENEWABLE ENERGY LABORATORY

ASTM Approval

June 2019	NREL/EPA Partnership Announced
Sept. 2019	Gen 1.5 Workshop
Winter 2019	Method Development
Spring 2020	DOE Nat'l Lab Round Robin
Spring 2020	NIST/NREL RR Analysis
June 2020	Method/Data Sent to EPA
Sept. 2022	EPA Issues Guidance

Cellulose (2021) 28:1989–2002
https://doi.org/10.1007/s10570-020-03652-2

ORIGINAL RESEARCH

Direct determination of cellulosic glucan content in starch-containing samples

Justin B. Sluiter · Katie P. Michel · Bennett Addison · Yining Zeng · William Michener · Alexander L. Paterson · Frédéric A. Perras · Edward J. Wolfrum

Received: 30 June 2020 / Accepted: 15 December 2020 / Published online: 15 January 2021

Abstract A simple and highly selective analytical procedure is presented for the determination of cellulosic glucan content in samples that contain both cellulose and starch. This method eliminates the unacceptably large compounding errors of current two-measurement methods. If both starch and cellulose are present before analytical hydrolysis, both will be hydrolyzed to glucose causing bias and inaccuracy in the method. To prevent this interference, the removal of starch prior to cellulosic quantification is crucial. The method presented here is a concise in-series procedure with minimal measurements, eliminating large compounding errors. Sample preparation consists of a starch extraction employing enzymatic hydrolysis followed by a simple filtration and wash. The samples are then subjected to a two-stage acid hydrolysis. The concentration of glucose is determined by ion exchange high-performance liquid chromatography with a Pb^{2+} column and a refractive index detector. The cellulosic glucan content is calculated based on the initial dry weight of the starting material. Data for the native biomass materials studied show excellent reproducibility, with coefficients of variance of 3.0% or less associated with the method. This selectivity for cellulosic glucan by the procedure was validated with several analytical techniques such as liquid chromatography coupled with mass spectrometry (LC–MS), Raman spectroscopy, and nuclear magnetic resonance.

Keywords Analytical · Carbohydrate · Cellulose · Glucose · Starch · Biofuels · Ethanol · DNP

Supplementary Information The online version contains supplementary material available at (https://doi.org/10.1007/s10570-020-03652-2).

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Introduction

Conversion of starch to ethanol is an ancient technology that is still used today at industrial scale to produce renewable ethanol as fuel. Because of its history, this well-established conversion of starch, an α-(1,4)-linked glucan carbohydrate, is often referred to as a first-generation technology. Conversion of cellulose, a β-(1,4)-linked glucan carbohydrate, to ethanol, has yet to be widely commercialized but has been extensively researched (Solomon et al. 2007; Orts and McMahan 2016). This technology is referred to as a second-generation technology. In the last decade, an interesting hybrid of these two conversion

Springer

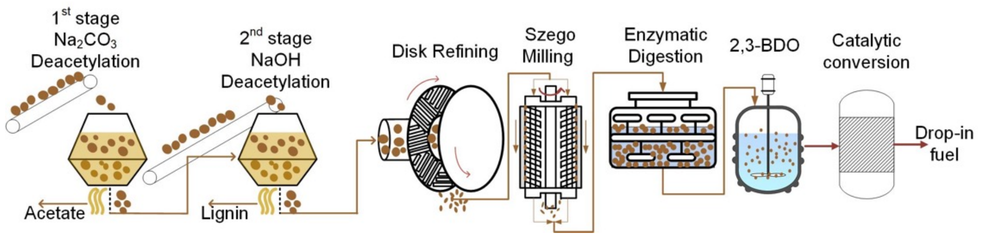
2021 Peer Review Feedback

Recommendations:

1) Increase use of LCA to guide research
2) Greater transparency in TEA methodology/assumptions
3) Clarify emphasis on DMR investments
4) Build a balance of early stage and deployment

Increase use of LCA to guide research

Examples of LCA analyses that are informing R&D priorities



	GHG* (CO_2e/kg)	Fossil Energy (MJ/kg)	Total Energy (MJ/kg)	Cost ($/lb)
NaOH (100%)	2.1	28.9	32.3	0.24
Na_2CO_3 (100%)	0.7	5.93	5.94	0.08

*The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET)

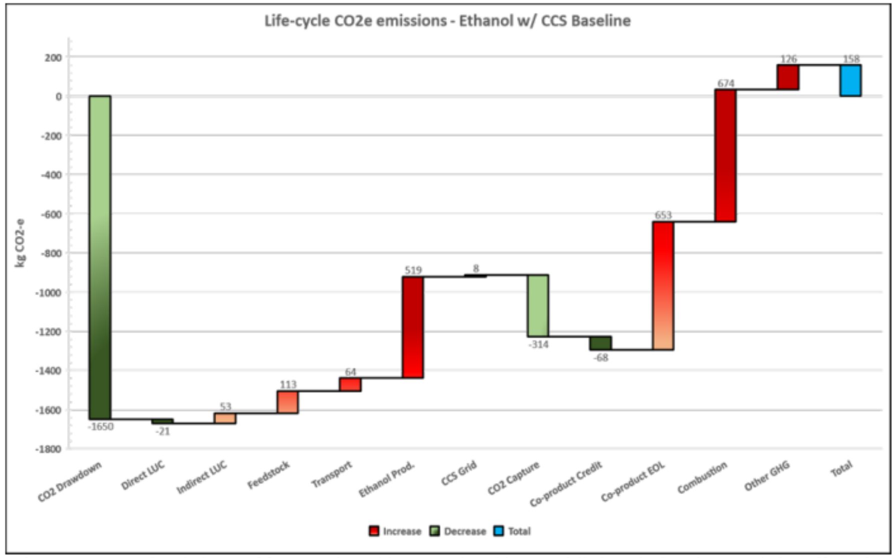


Figure 6. LCA carbon balance of fermentation with CCS only.

Topic Area 2: Affordable, Clean Cellulosic Sugars for High Yield Conversion Overview

Topic Area 2 Specific Requirements

- GHG emissions tracked in gCO2e/lb sugars;
- Water consumption tracked in gallons water/lb sugars; and
- Carbon intensity of the process

TEA Methodology

Examples of standardized assumptions and publicly available TEA tools

Biorefinery Analysis Process Models

NREL Transforming ENERGY

THIS PAGE IS TO DISTRIBUTE THIS INFORMATION TO THE PUBLIC
To save files to local computer, right click on link and choose "Save Target As...". For Aspen Plus BKP files, replace ".tiff" file name extension with ".bkp".

NOTICE: All information on this page is subject to a disclaimer.

Last Updated: November 2018

Algae Production via Open Pond Cultivation: NREL Algae Farm Model (Excel TEA Tool)

Contacts: Ryan Davis and Jennifer Clippinger

2016 Algae Farm Design Report of Davis et al. [PDF]

- Excel Spreadsheet

NREL 2017 Biochemical Sugar Model

Contacts: Ling Tao and Ryan Davis

- BKP File (Built in Aspen Plus V7.2)
- Excel Spreadsheet
- Readme Summary Sheet

Process Design for Biochemical Conversion of Biomass to Ethanol (2002 and 2011 Design Reports)

Contacts: Ling Tao and Ryan Davis

2011 Design Report of Humbird et al. [PDF]

DW1102A — Files supporting the 2011 Design Report

Tables in the spreadsheet may differ slightly from those in the report due to small errors corrected after publication.

- BKP File (Requires Aspen Plus V7.2; does not require NREL databanks or Fortran compiler)
- Excel Spreadsheet with Macros (Requires Excel 2007 or later)

DW1107A – Direct Port of DW1102A to Aspen Plus V7.3

- BKP File (Requires Aspen Plus V7.3)
- Excel Spreadsheet with Macros (Requires Excel 2007 or later)

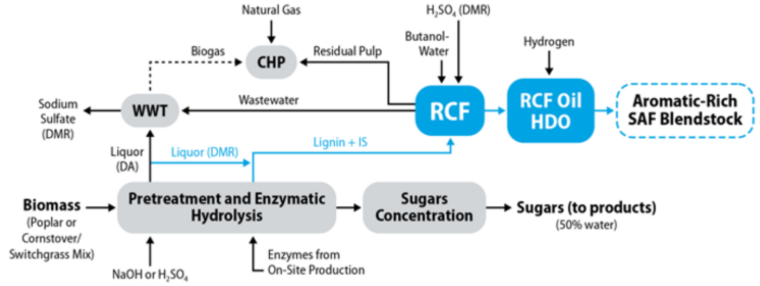
[Biorefinery Analysis Process Models | NREL]

Topic Area 2: Affordable, Clean Cellulosic Sugars for High Yield Conversion Overview

Topic Area 2 Specific Requirements

- Provide a techno-economic analysis to calculate the minimum sugar selling price including:
  - Cost of enzyme production and/or purchase
  - Capital and operating costs to produce monomeric sugars
  - Assuming a delivered feedstock cost of $86/ton

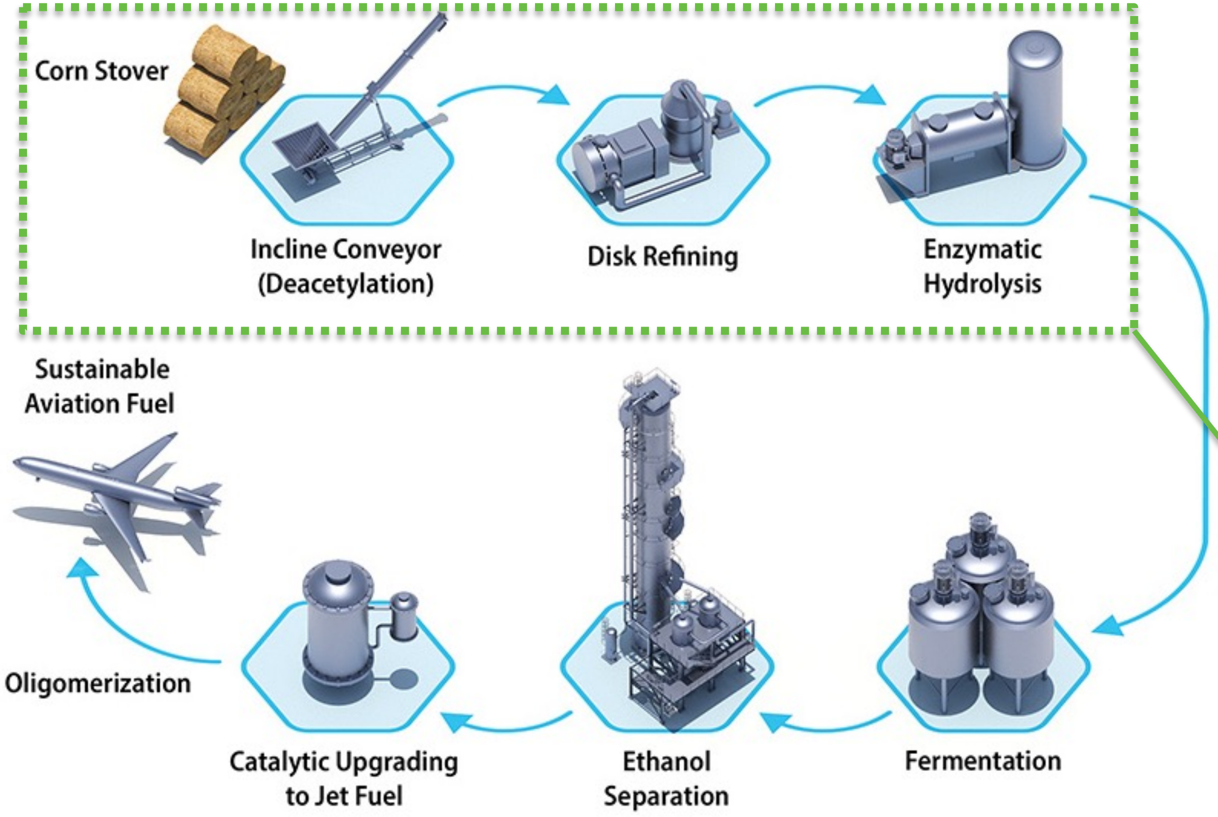
Increased emphasis on "smaller system boundary" TEA



Case	Feedstock	Pretreatment and enzymatic hydrolysis	Minimum sugars selling price ($/kg)	GHG emissions[1] (gCO_2e/MJ SAF)	GHG emission reduction
1	Poplar	DAP-EH	0.33	19	77%
2	Corn stover	DAP-EH	0.37	16	81%
3	Poplar	DMR-EH	0.53	35	59%
4	Corn stover	DMR-EH	0.60	39	54%

Why the Emphasis on DMR?

Deacetylation and Mechanical Refining (DMR)



electrek

Southwest Airlines is investing in a sustainable aviation fuel pilot program

Michelle Lewis | Jun 3 2022 - 3:02 pm PT | 0 Comments

DALLAS INNOVATES

Southwest Airlines Invests in Startup That's Turning Corn Waste into Jet Fuel

As part of a Department of Energy-backed effort, Dallas-based Southwest Airlines is investing in SAFFiRE Renewables, a new startup that aims to turn corn waste into sustainable aviation fuel.

BIOMASS MAGAZINE

Biden administration takes action to expand SAF production, use

By Erin Voegele | September 09, 2021

BETO investments in the Pretreatment and Process Hydrolysis and Low-Temperature Advanced Deconstruction Projects 2014-2022

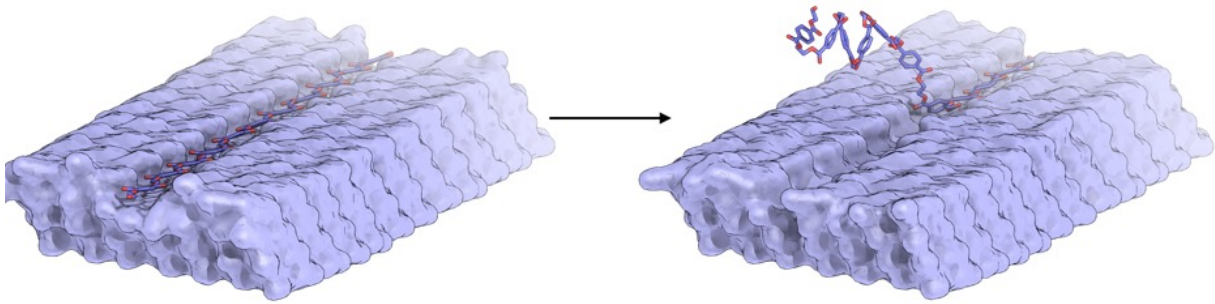
D3MAX advancebio SYSTEMS LLC LanzaJet NREL NATIONAL RENEWABLE ENERGY LABORATORY

Ensure a Balance of Early and Applied TRL Work

“Therefore, this should not become an either/or for fundamental research versus applied science and large-scale demonstrations. The most powerful combination of activities for BETO would be the retention of the strong scientific program that BETO has built while advocating for new projects to support what appears to be a strong administration interest in large-scale demonstration.”
-2021 Biochemical Conversion and Lignin Utilization Panel

Examples of fundamental R&D that are critical for applied R&D projects:

Analysis/Crosscutting Activities

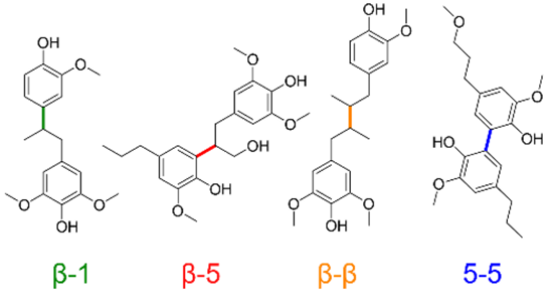


Polymer chain in crystal surface   Polymer chain extracted from surface

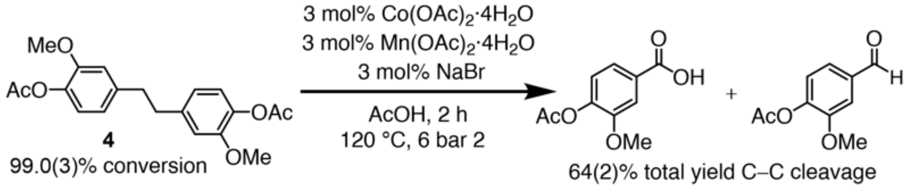
Molecular dynamics based procedure to compute the free energy to decrystallize a single chain.
Decrystallization is the first step in many depolymerization processes, including biological routes (e.g. PETase).

Lignin Utilization

Exemplary C-C bonds in lignin that catalytic approaches must cleave



Exemplary C–C bonds in lignin that catalytic approaches must cleave



Gu, Palumbo, Bleem *et al. in review*

Questions

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