Advanced Biomass to Gasoline Technology

May 24th. 2013

Bio-Oil Technology Area Review

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Exelus Inc.

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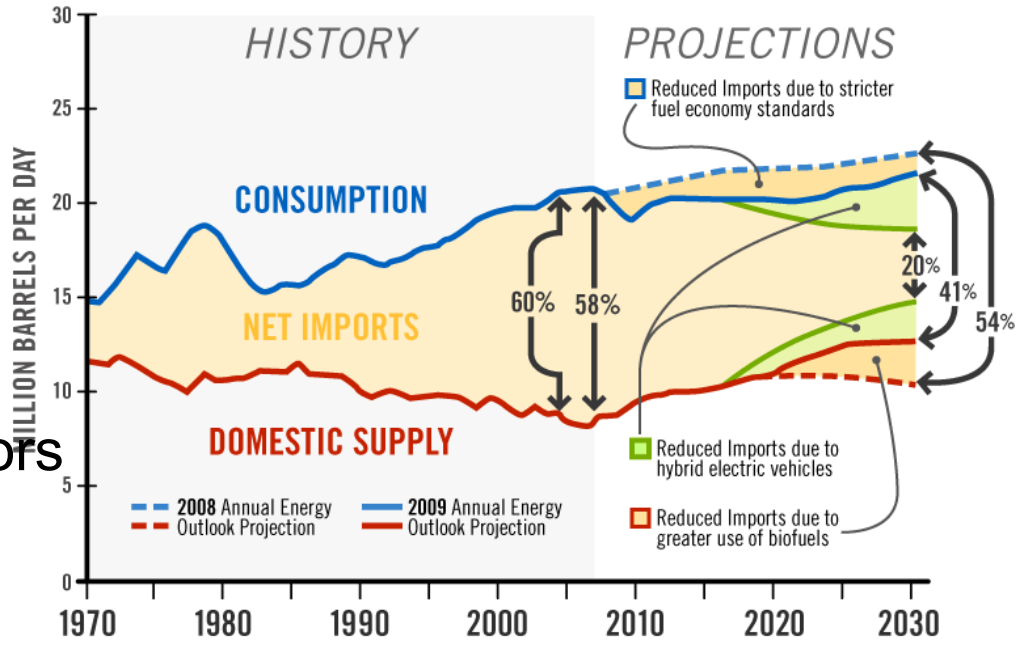
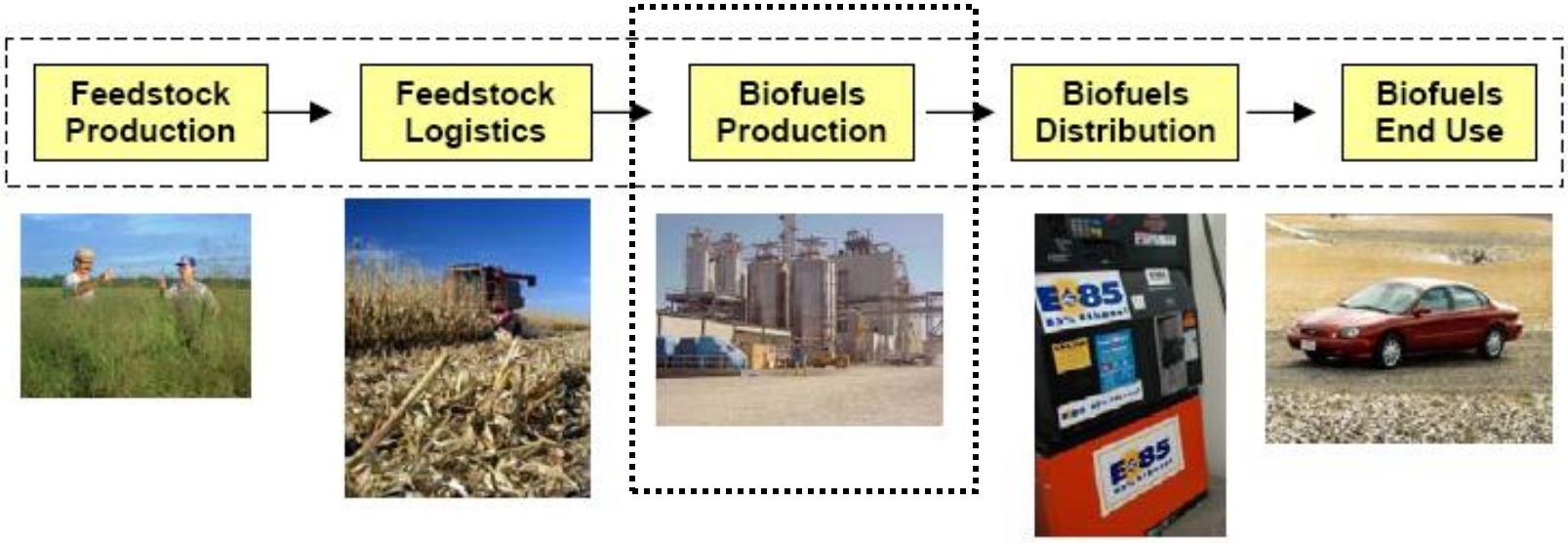
Outline

- Objectives
- Project Overview
- Technical Approach
- Summary of Results
- Relevance
- Critical Success Factors
- Future Work
- Summary



Goal Statement

- Project seeks to develop a low-temperature chemical process to convert cellulosic biomass into a gasoline blend-stock
- Key innovations in this technology are
  - Novel biomass deconstruction scheme &
  - Engineered catalysts that convert the de-polymerized biomass into alcohols as high-octane gasoline additives



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FOA Objectives

The objectives of this FOA are to develop:

- Technologies and processes necessary for abundant commercial production of bio-fuels at prices competitive with fossil fuels;
- High-value bio-based products:
  - to enhance the economic viability of bio-fuels and power;
  - to serve as substitutes for petroleum-based feedstocks and products; and
  - to enhance the value of co-products produced using the technologies and processes; and
- A diversity of economically and environmentally sustainable domestic sources of renewable biomass for conversion to bio-fuels, bio-energy and bio-based products.

Quad Chart

Timeline

Start - September 1, 2010

End - August 31, 2013

Percent complete = 90%

Barriers

1. Glucose Decomposition
2. High H_2 Consumption
3. Dilute product concentration

Budget

- Total project funding
  - DOE share = $1.2 million
  - Contractor share = $0.4 million
- Funding received so far
  - DOE = $ 1.0 million
  - Project Partners = $0.5 million
- ARRA Funding = 0

Partners

ZEOLYST INTERNATIONAL

MUSTANG

PRINCETON UNIVERSITY

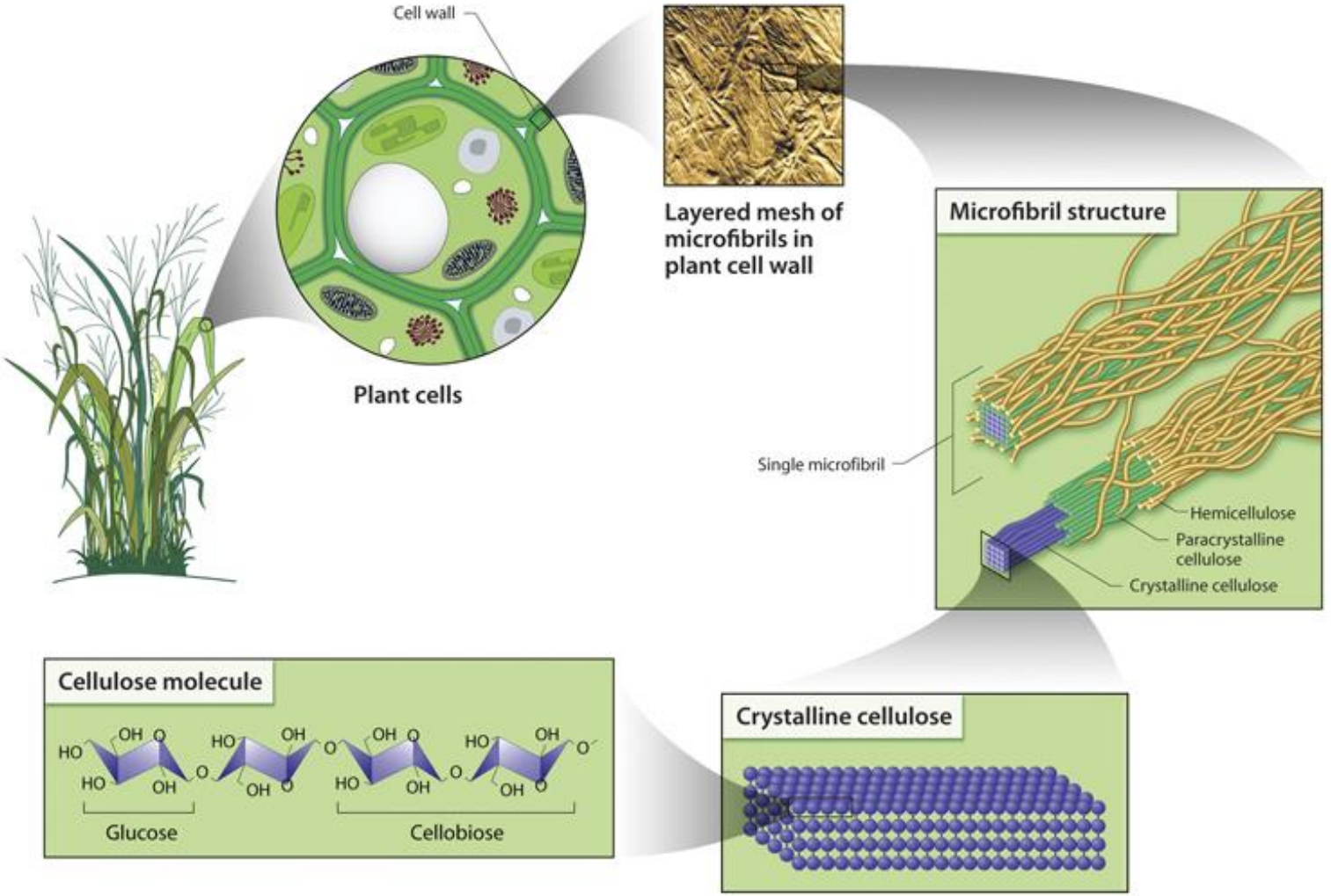
Project Overview

Biomass Structure

Conventional Processes

Exelus Approach & Targets

Biomass has Complex Structure



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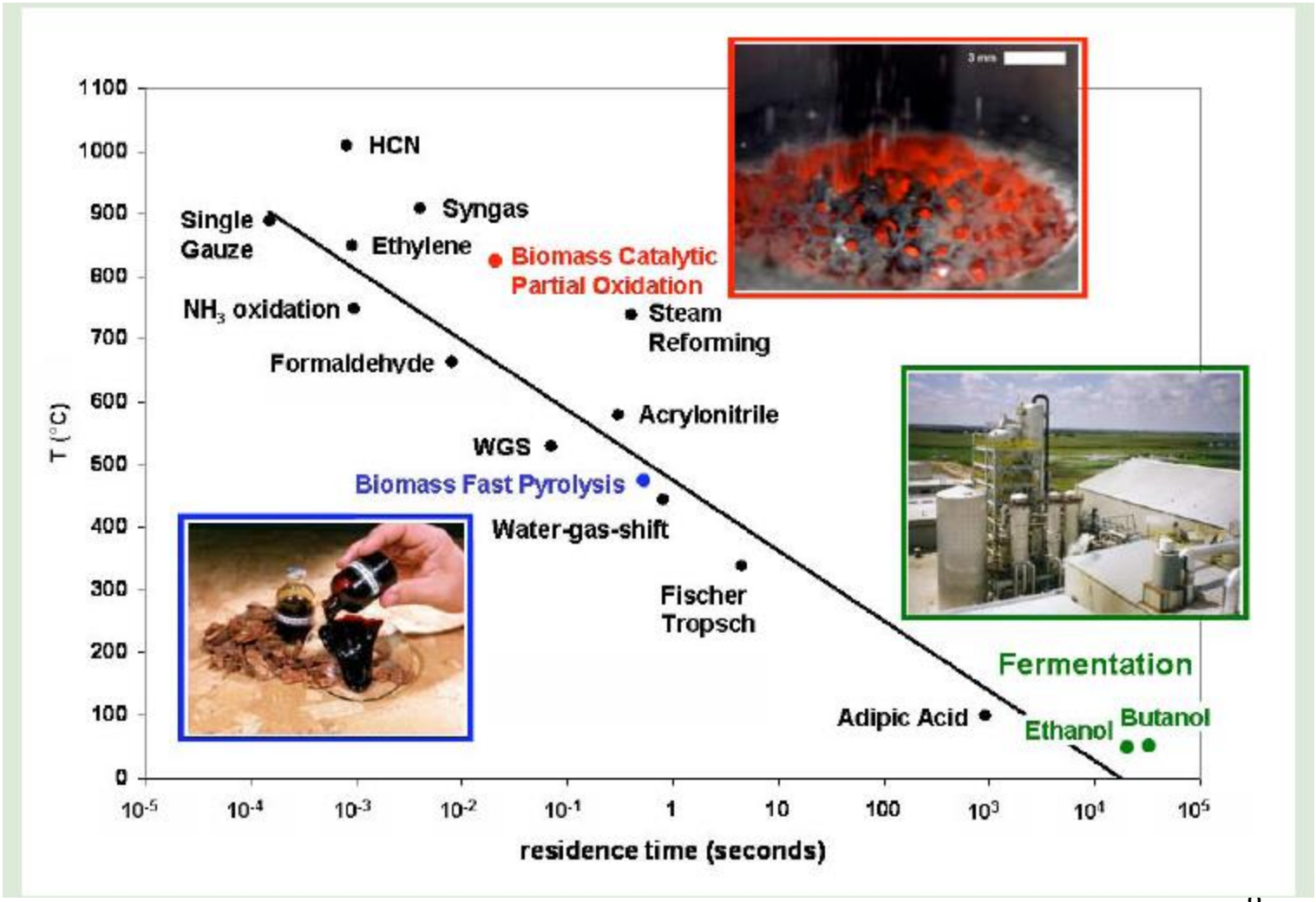
Typical Approach



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E^3 Constraints

New process technologies must address all three aspects of modern fuel manufacturing:

Energy

Economics

Environment

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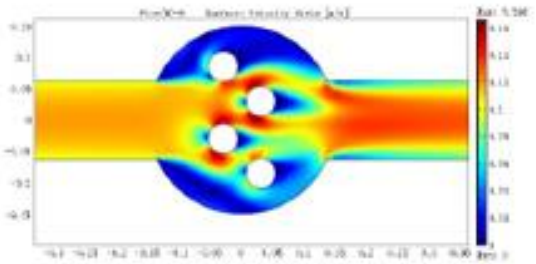
Process Wish-list

- Mild operating conditions
  - Low Temperatures (< 250°C)
  - Modest Pressures (< 40 bar)
- Simple processing steps
  - Fixed-bed reactors
  - Conventional unit operations
- Inexpensive catalysts
  - Minimize use of precious metal catalysts
  - No hazardous liquid acids
- Modest utility requirements
  - No biomass drying step
  - Product concentrations > 20 wt% in water



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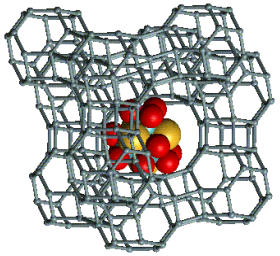
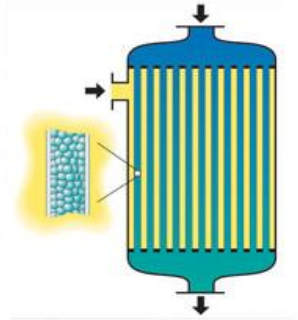
Integrated Approach

Catalyst



Reactor



Process

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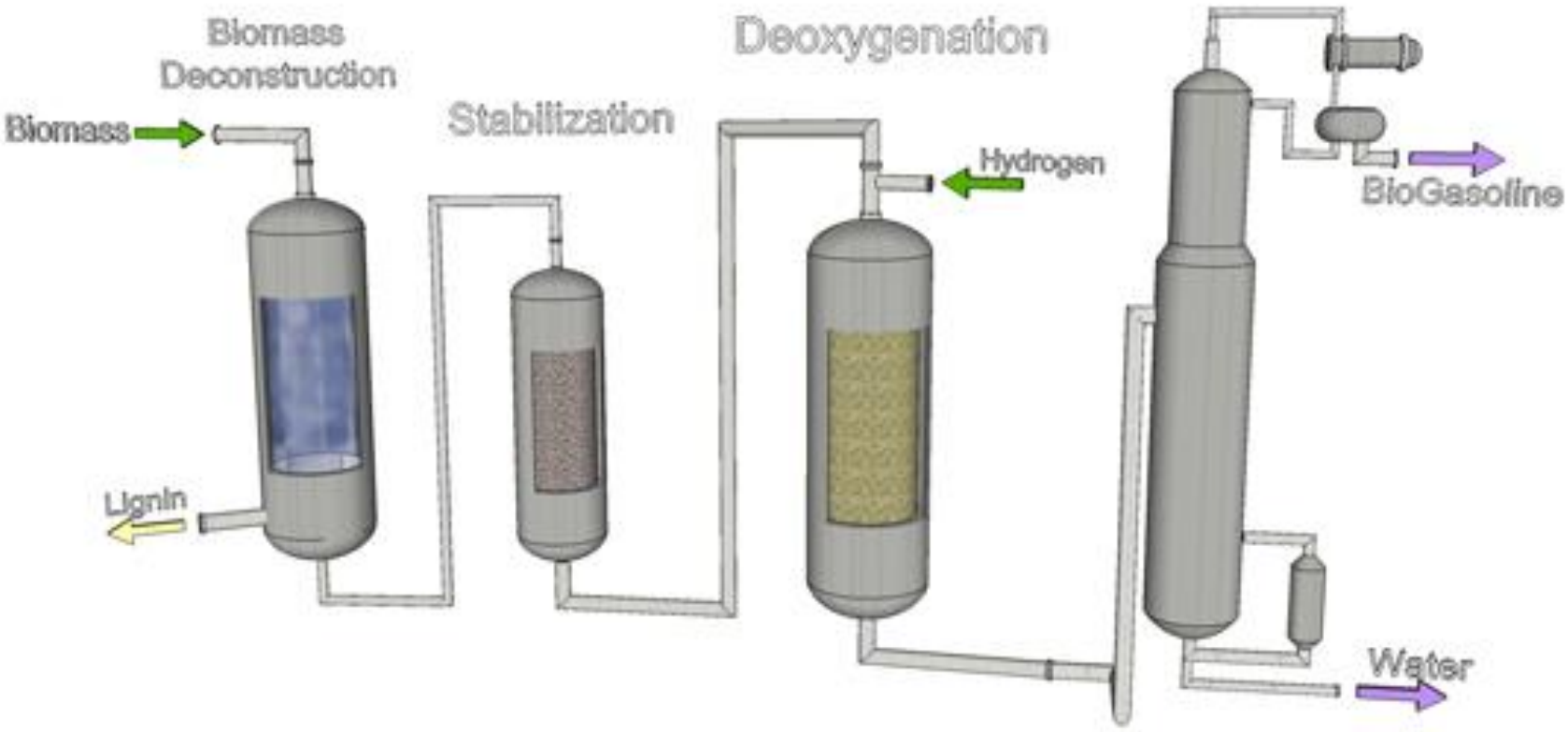
Exelus Process Overview



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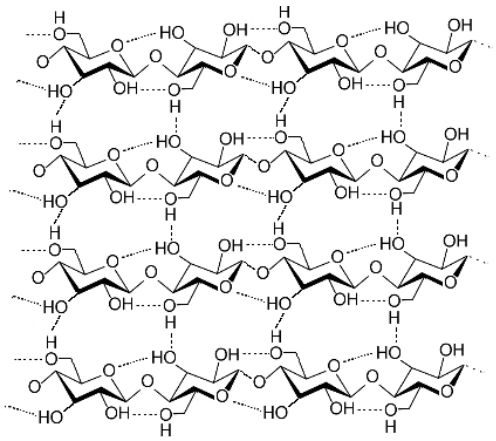
Technical Approach

Exelus Approach

Technical Targets

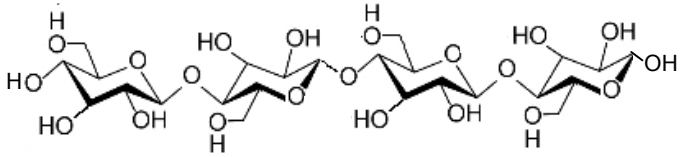
Major Mile-stones

Biomass-to-Gasoline Process



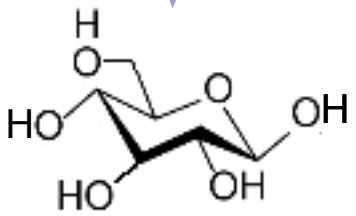
Cellulose Crystal

De-crystalization &
De-polymerization



Glucose Oligomers

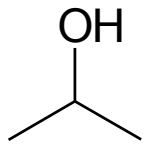
Hydrolysis



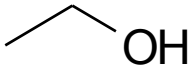
Glucose

Deoxygenation
& Cracking

BioGasoline



Isopropanol



Ethanol

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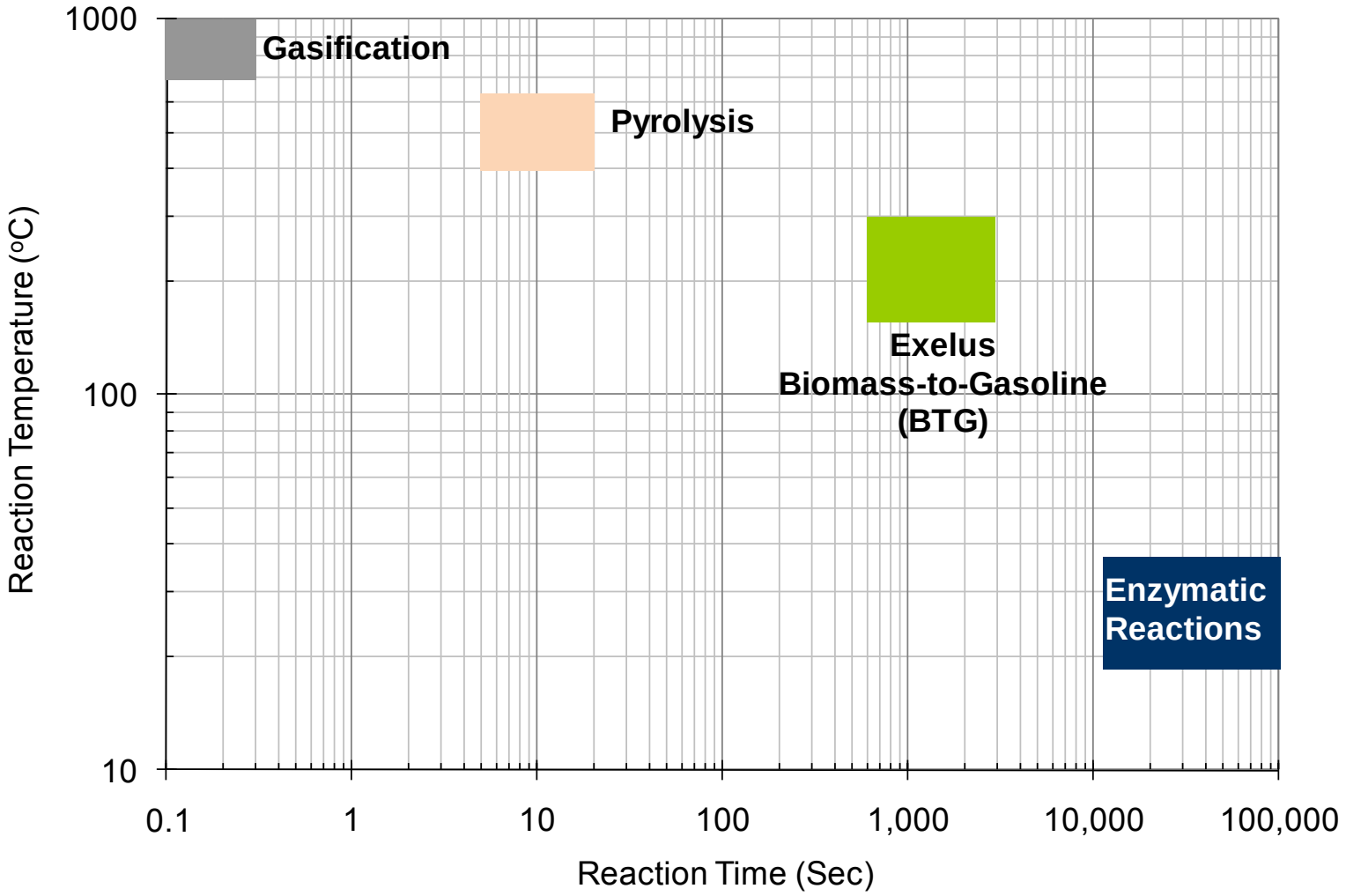
Finding the Middle Ground



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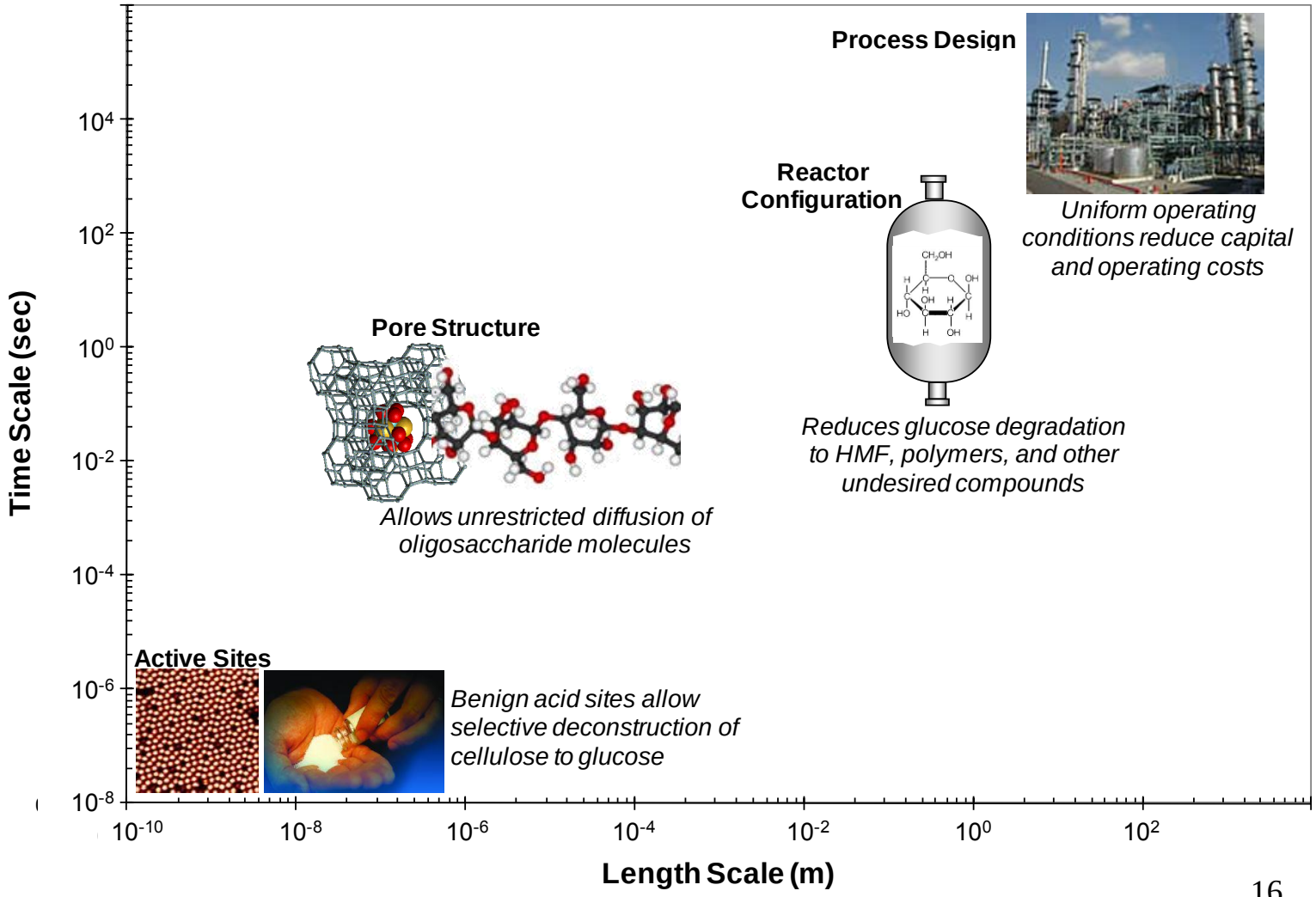
Innovations



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Overall Chemistry

Propanol

$$C_6H_{10}O_5 + 6\ H_2 \rightarrow 2\ C_3H_8O + 3\ H_2O$$

Cellulose Monomer | Hydrogen | Propanol | Water

ΔH_f° = -186.5 kJ/mol propanol

Ethanol

$$C_6H_{10}O_5 + 6\ H_2 \rightarrow 3\ C_2H_6O + 2\ H_2O$$

Cellulose Monomer | Hydrogen | Ethanol | Water

ΔH_f° = -103.4 kJ/mol ethanol

Technical Targets & Barriers

Key Variables	Technical Target	Associated Barriers
Overall Process Performance (All Reactions Combined)		
Productivity	>150 g biomass converted / m^3 catalyst /sec per reaction	Reduced activity in low-cost catalysts Rate of cellulose decomposition
Selectivity	>70% Selectivity to alcohols	Methanation, reforming & etherification rxns
Stability	< 1 kg catalyst consumed / ton alcohols produced	Catalyst coking, corrosion under hydrothermal conditions
Catalyst Cost	< $100 /kg	Precious metal content
Capital Requirements	Less than $8000 per barrel-per-day capacity	Separation requirements, reactor volume and configuration, process severity
Total Cost of Production	Less than $2.00 /gal alcohol product	Distillation costs, hydrogen requirement, energy inputs, process selectivity

Experimental Results

Cellulose Deconstruction

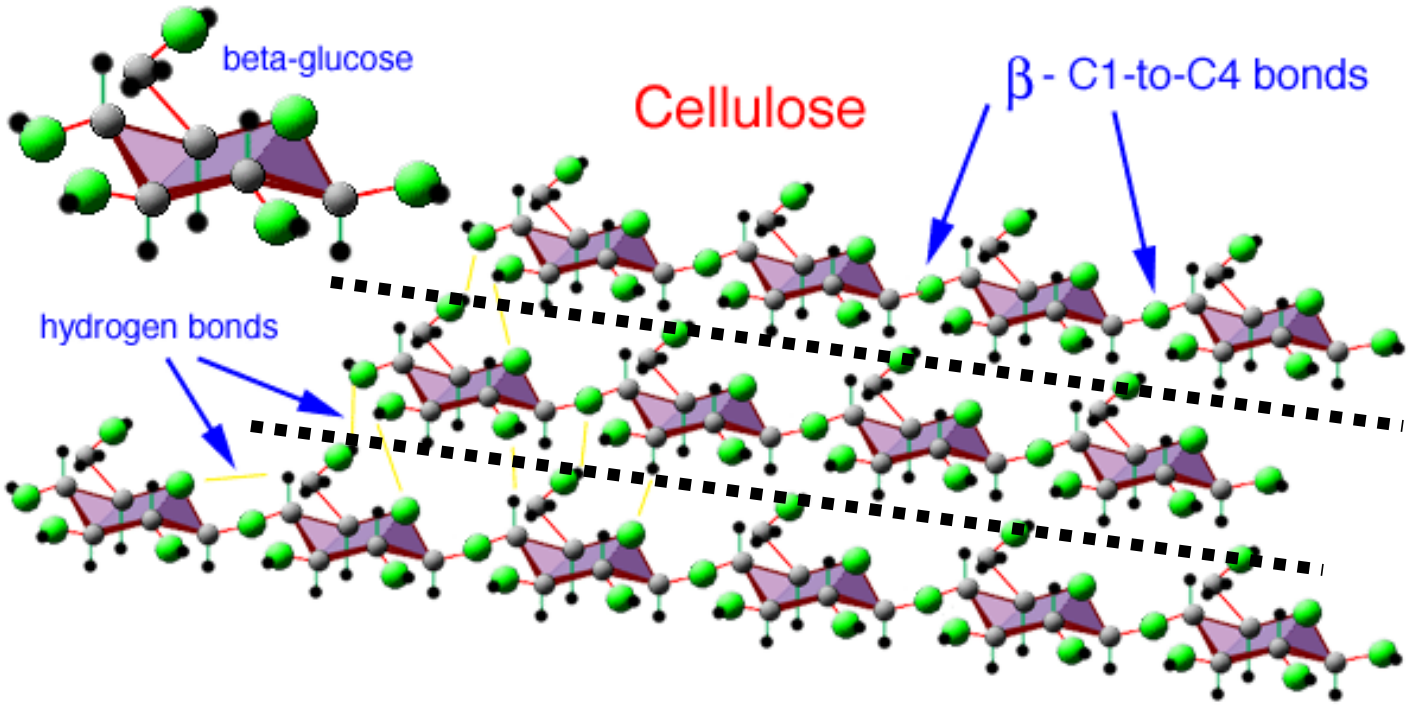
Oligosaccharide Hydrolysis

Glucose Cracking/De-oxygenation

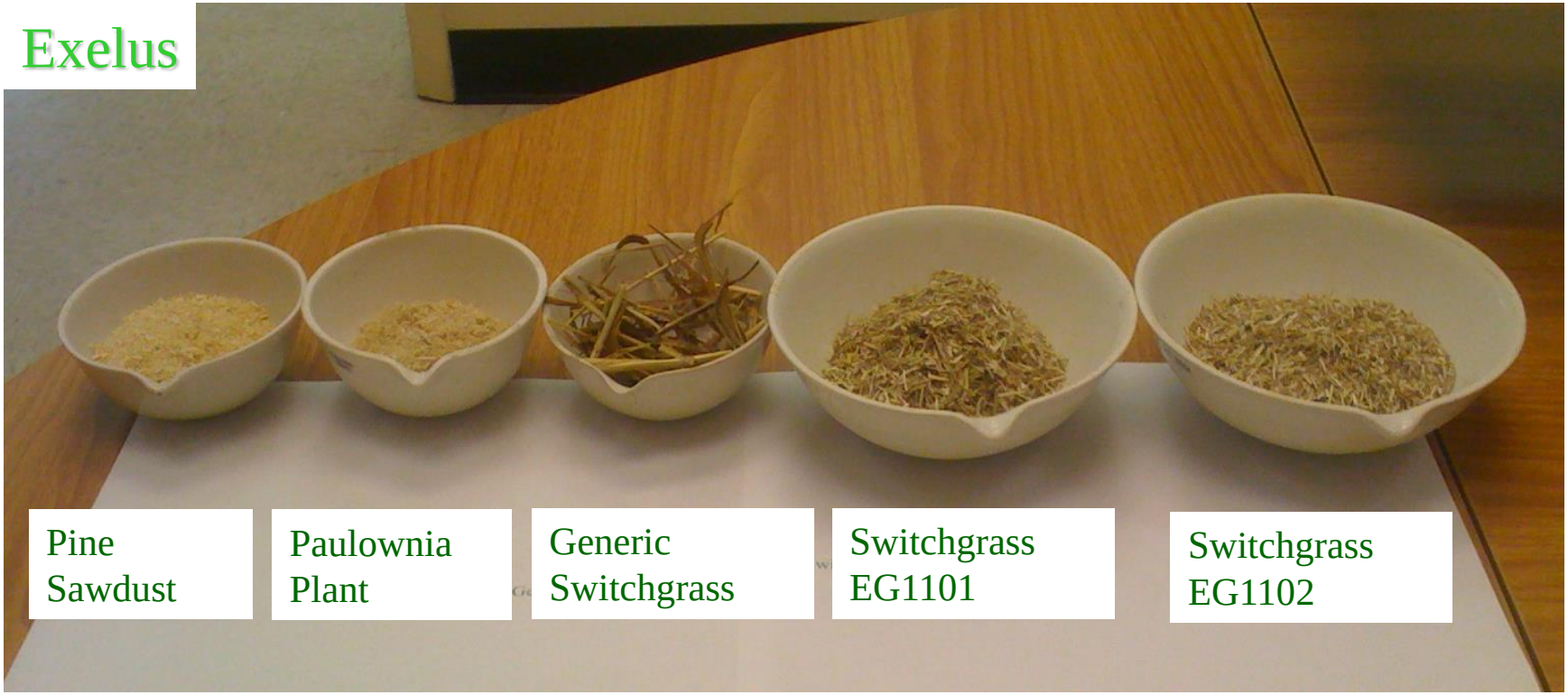
Stability Test

Step 1: Cellulose Deconstruction

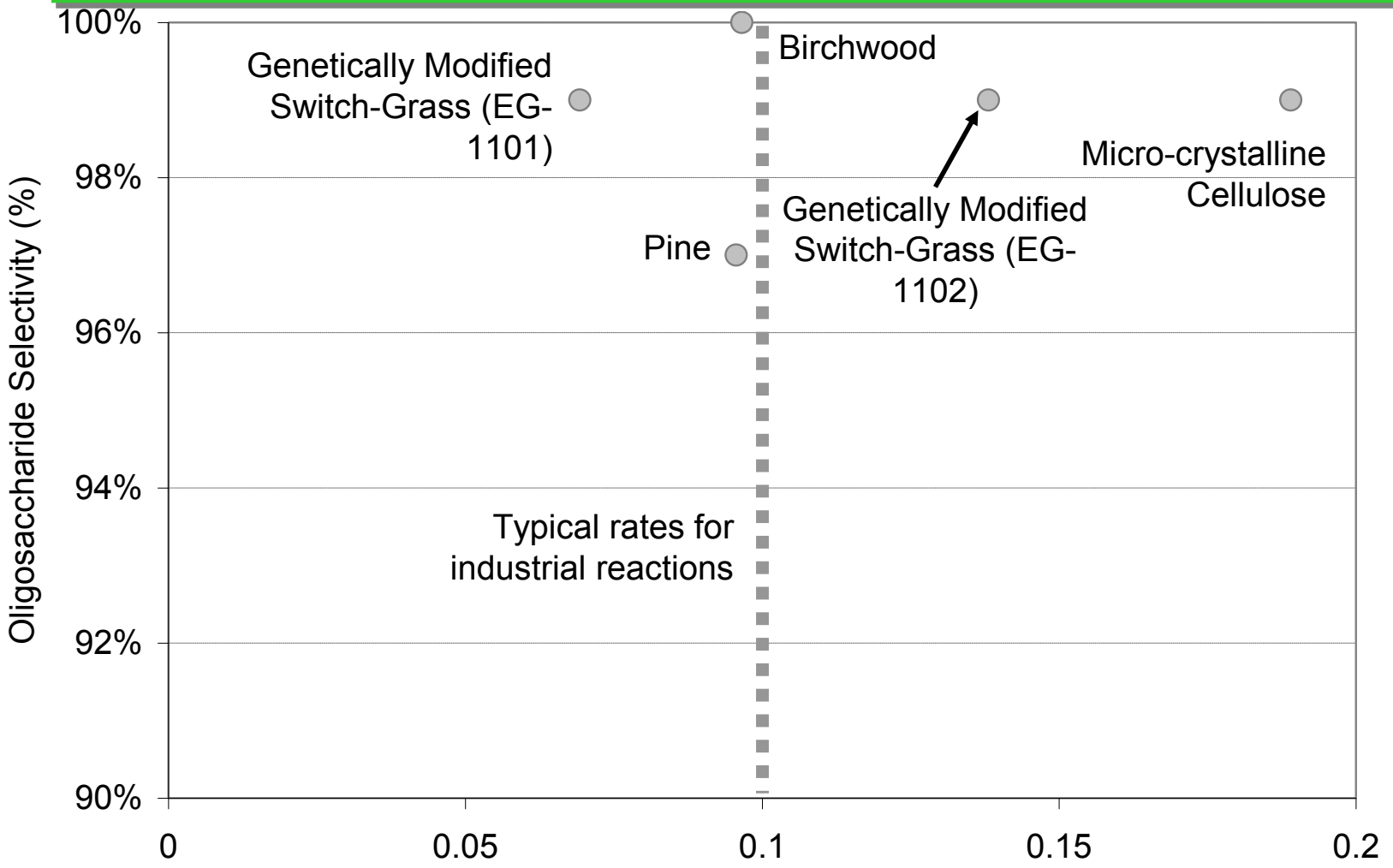
Breaking the hydrogen bonds



Types of Biomass Tested



Feedstock Flexibility



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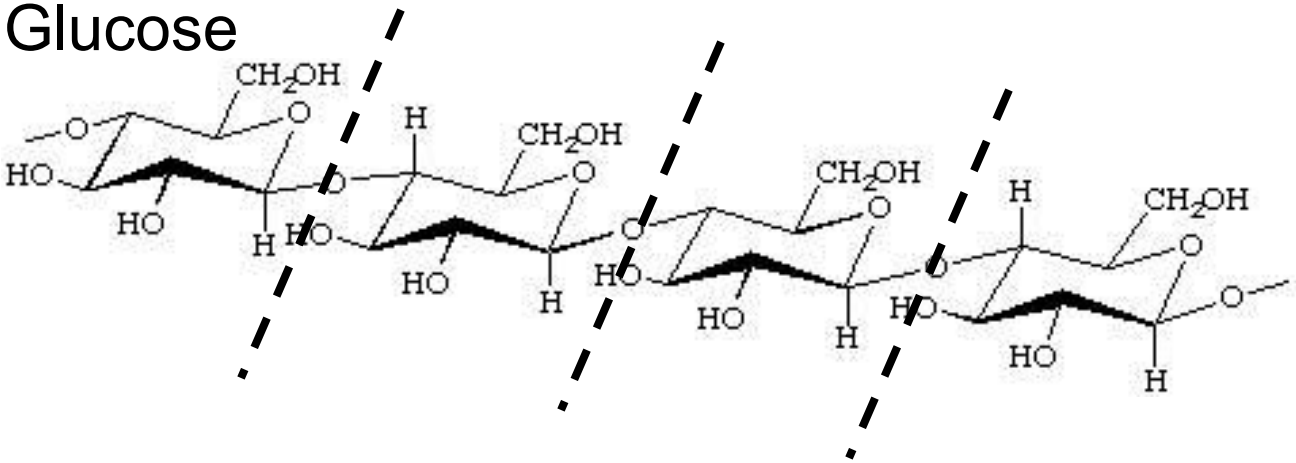
Step 2: Oligosaccharide Hydrolysis

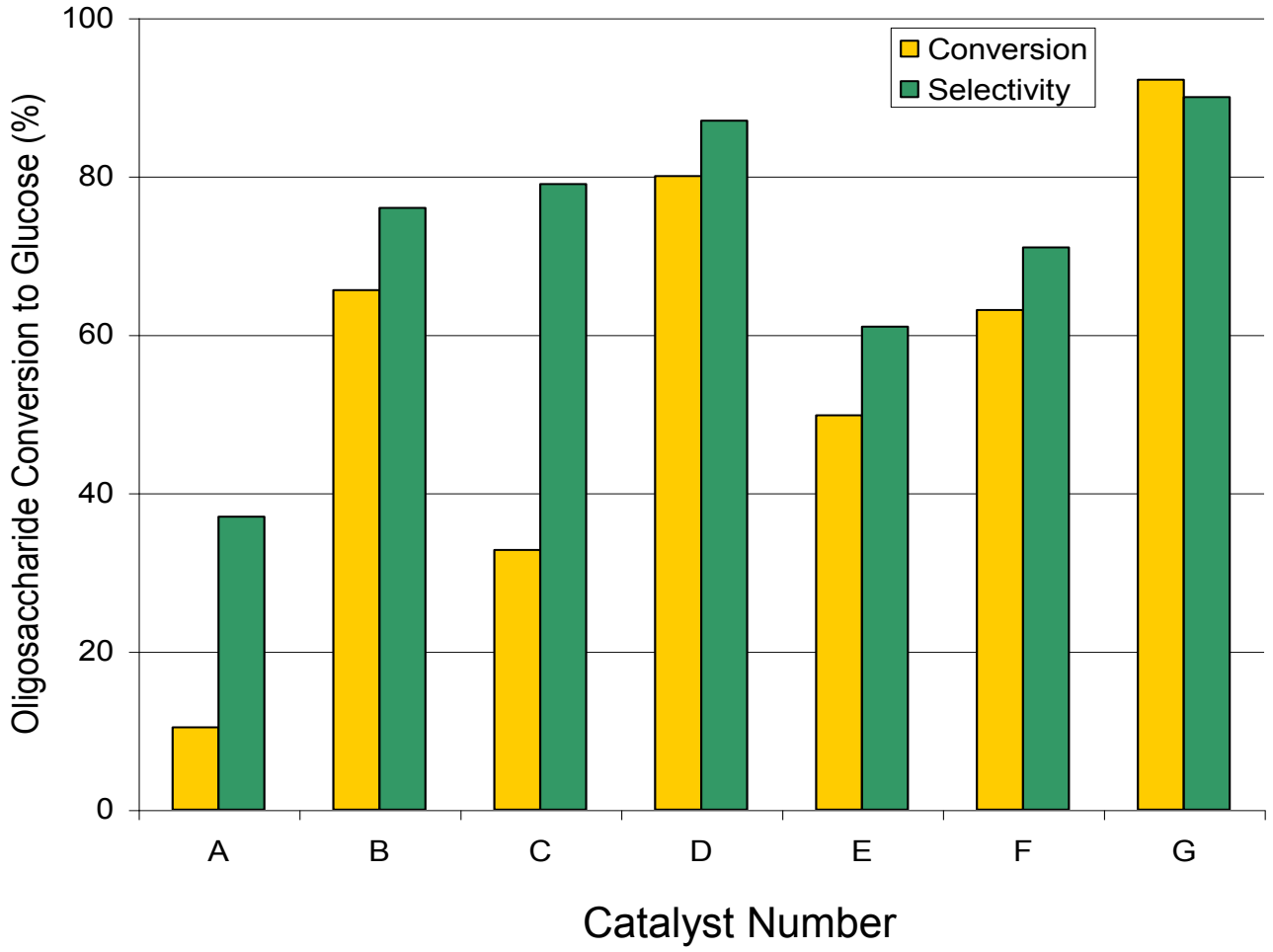
Breaking the β-bonds

Glucose



Oligosaccharide

Step 2: Catalyst Screening Results



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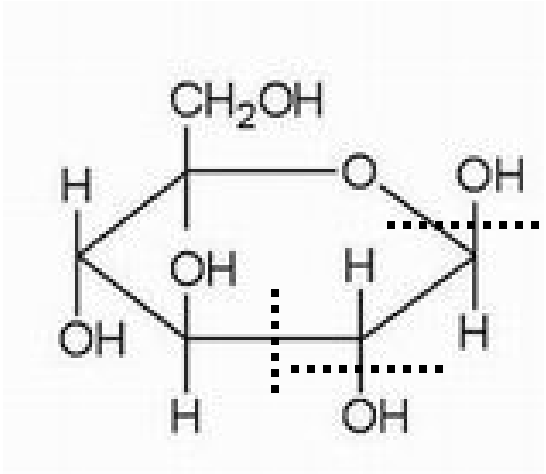
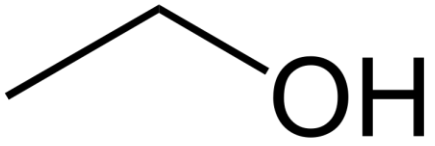
Step 3: Cracking and De-oxygenation

Breaking C-C and C-O bonds



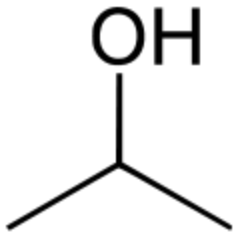
Glucose

H_2



Ethanol

H_2



Iso-Propanol

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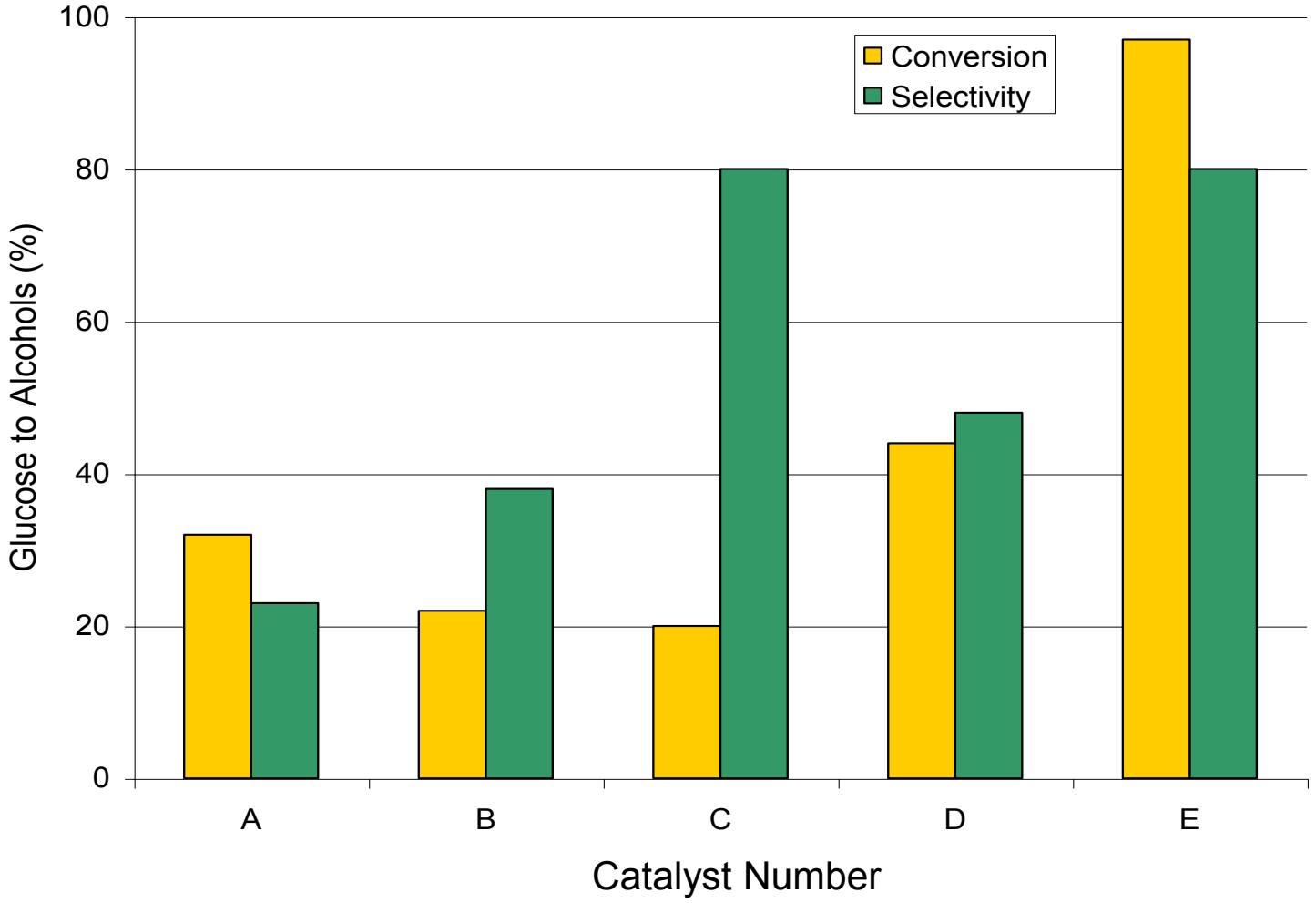
Step 3: Catalyst Screening Results



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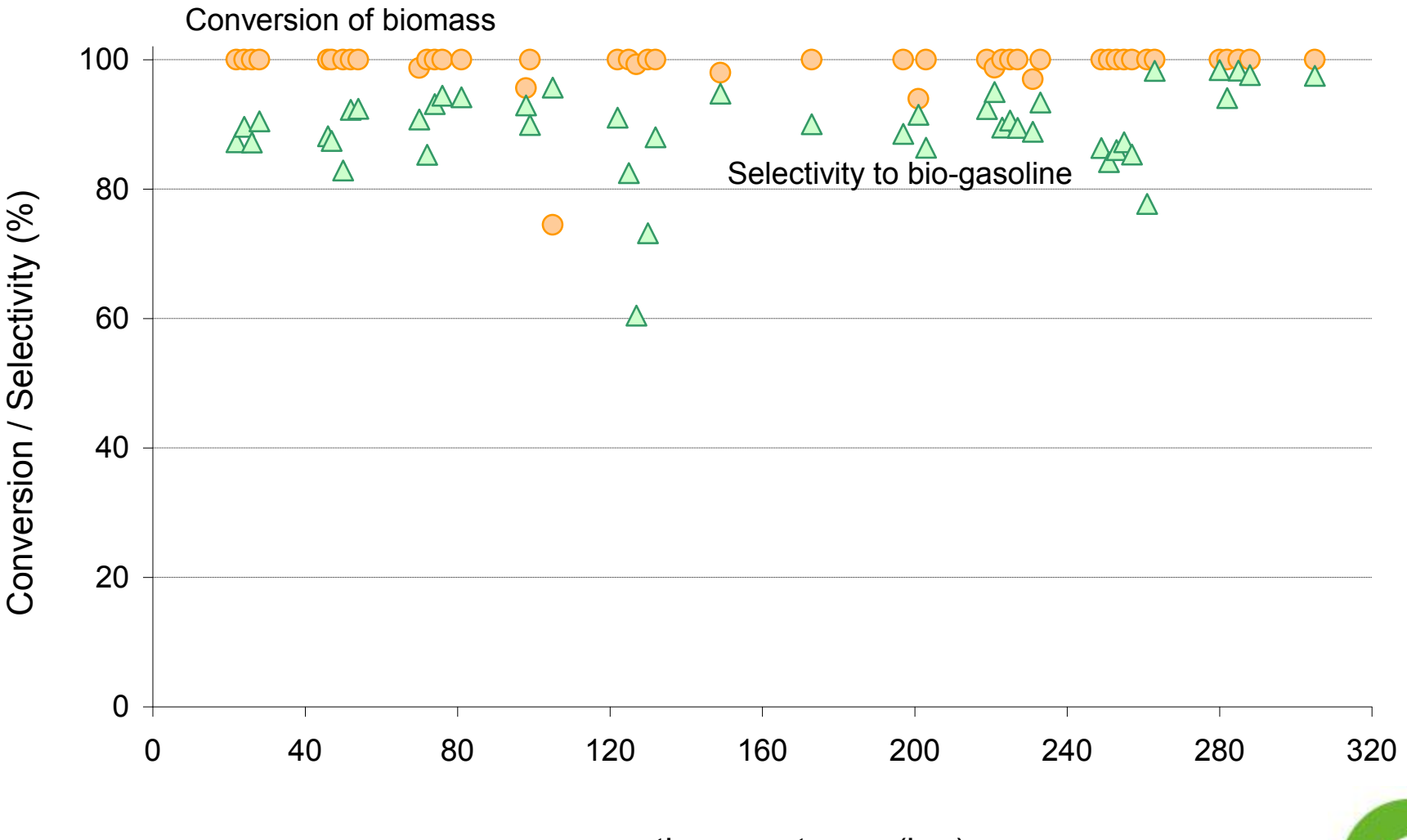
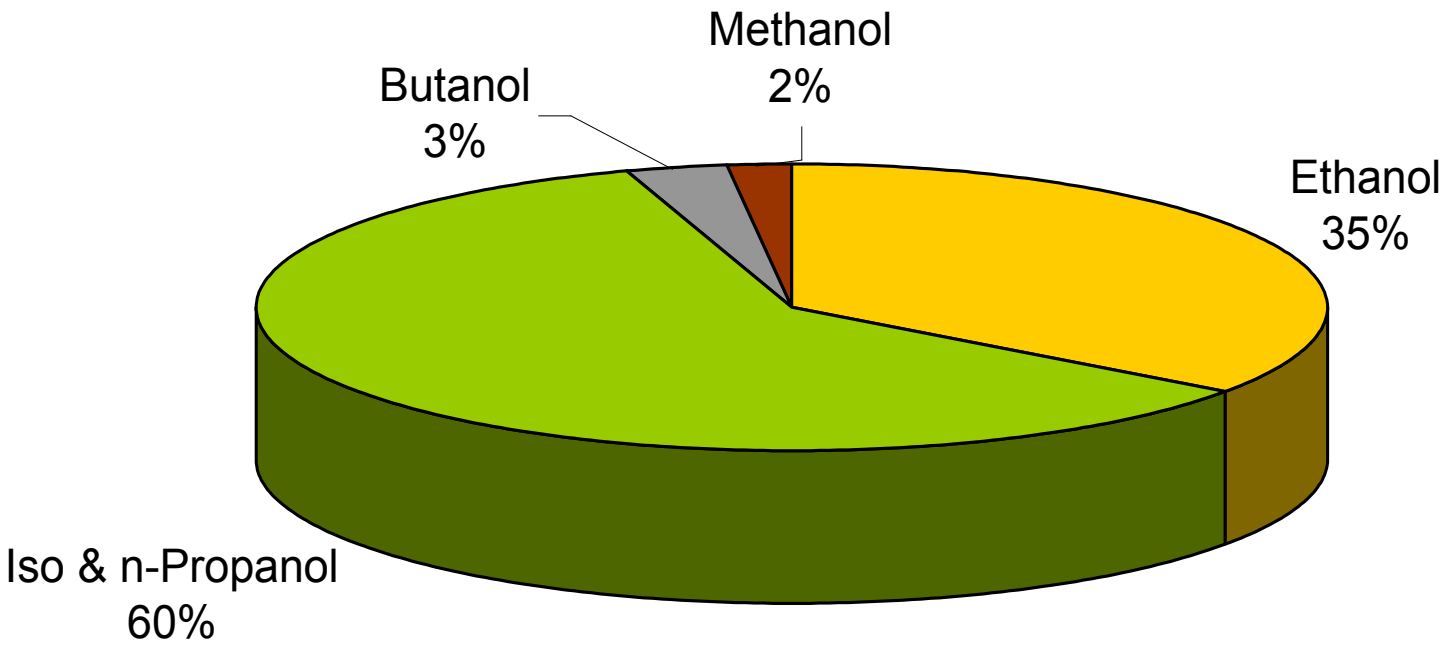
Integrated Test Unit

Integrated Stability Test Results



Bio-Gasoline Composition



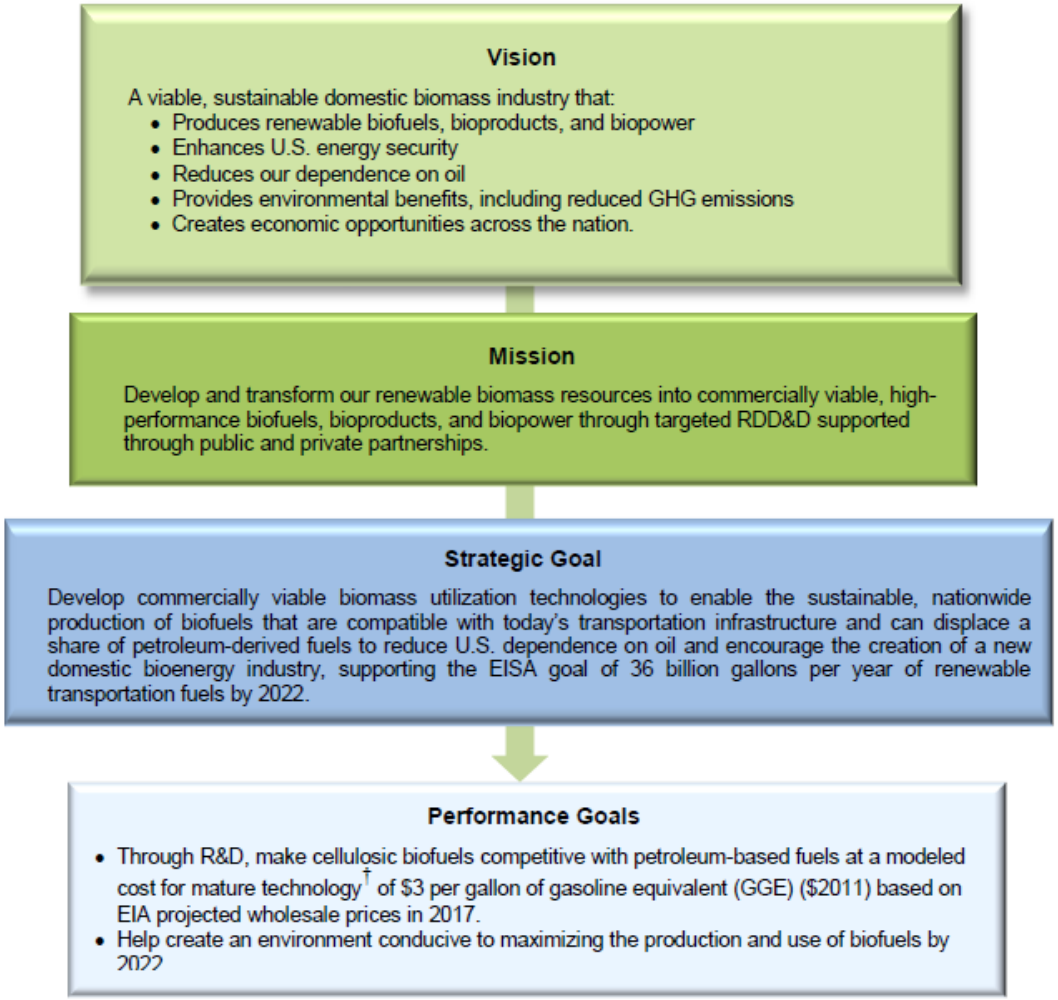
Project Relevance

MYPP Mission & Goals

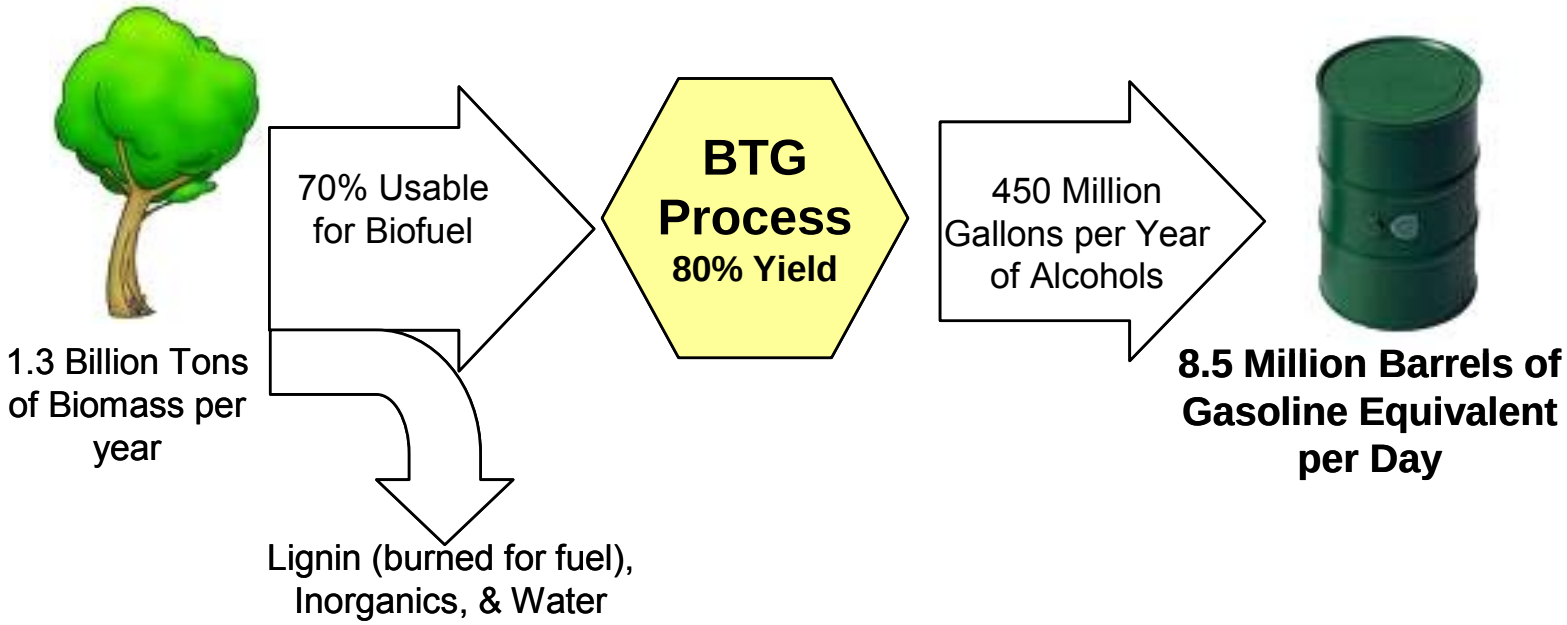
Project Relevance

Approach to meeting targets

MYPP Mission & Goals



Project Relevance



Estimated Bio-Gasoline Cost = $2.00/gal

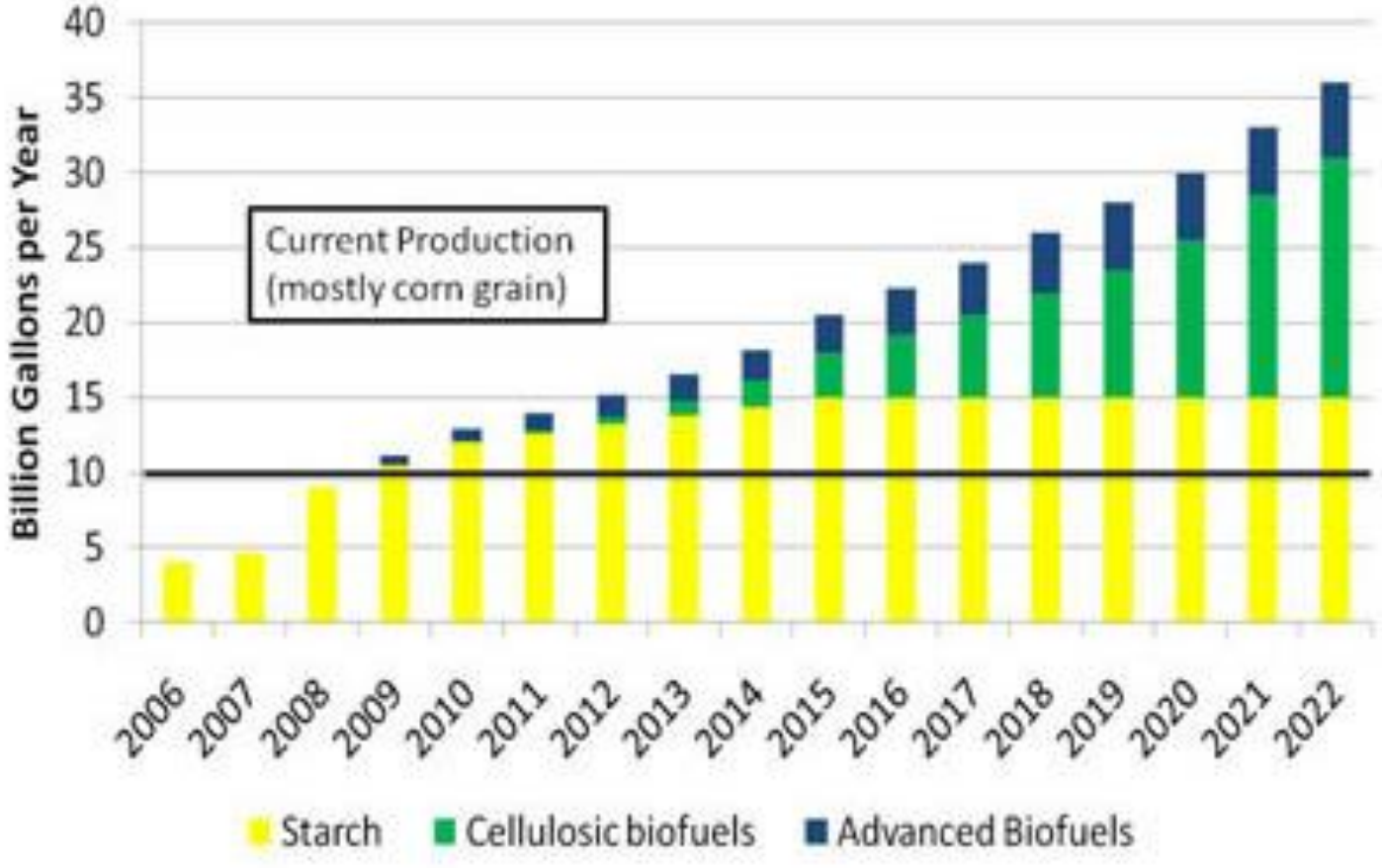
Approach to meeting project targets

Exelus Approach	Advantages	Benefits
Liquid Phase Processing	No expensive solvents required "Green" process Ability to use wet biomass	Reduced energy consumption Feedstock flexibility
Heterogeneous Catalysts	No neutralization required No acid migration through process Simple separation of catalyst and process streams	Low operating costs Low equipment costs
Engineered Catalyst Functionality	Intensifies and simplifies process by eliminating multiple separation steps. Minimize coke, acid and polymer formation High overall selectivity	Low capital cost High catalyst stability Efficient conversion of feedstock
Novel Process Chemistry	High carbon efficiency and retention of 94% of input chemical energy	Highly efficient process

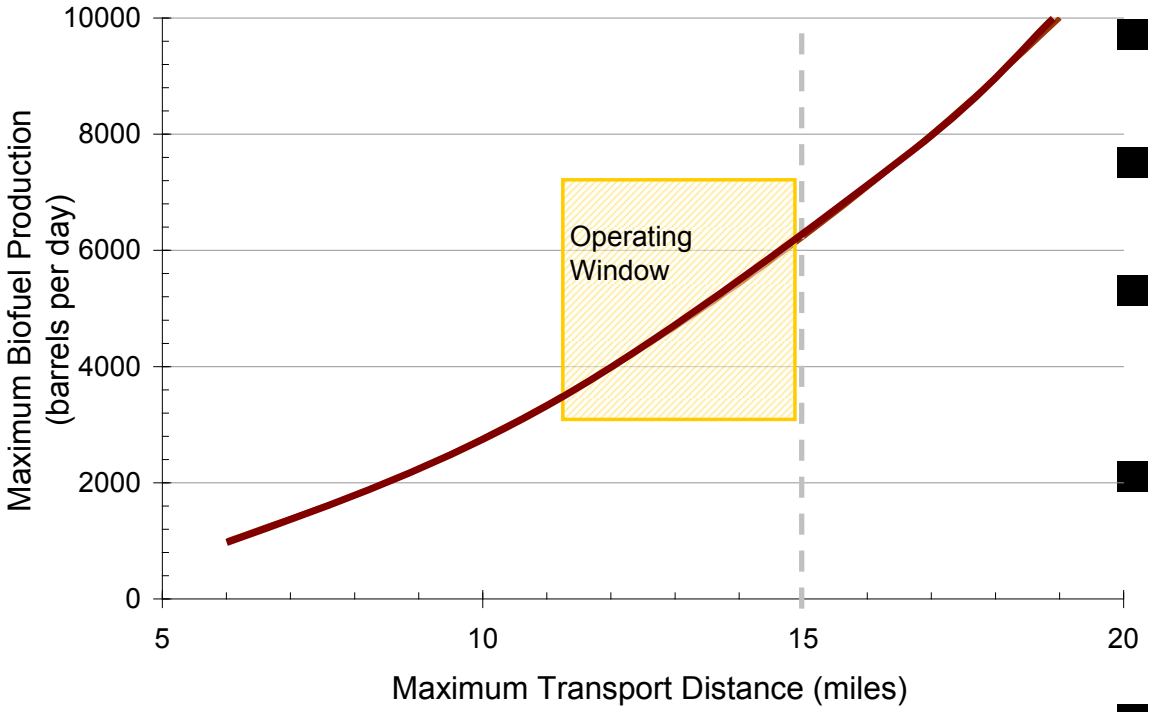
Critical Success Factors

RFS Mandates
Biomass Logistics
Capital Cost
Variable Cost of Production

RFS Mandate


Billion Gallons per Year
40
35
30
25
20
15
10
5
0
Current Production
(mostly corn grain)
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
Starch
Cellulosic biofuels
Advanced Biofuels

Biomass Logistics



- Biomass is a diffuse energy source
- Has low energy content per unit mass and unit volume
- Is limited in the amount that can be produced per unit land area.
- Transporting biomass over large distances is energy-inefficient and economically prohibitive
- Feeding solid bio-mass to reactors under pressure is a challenge

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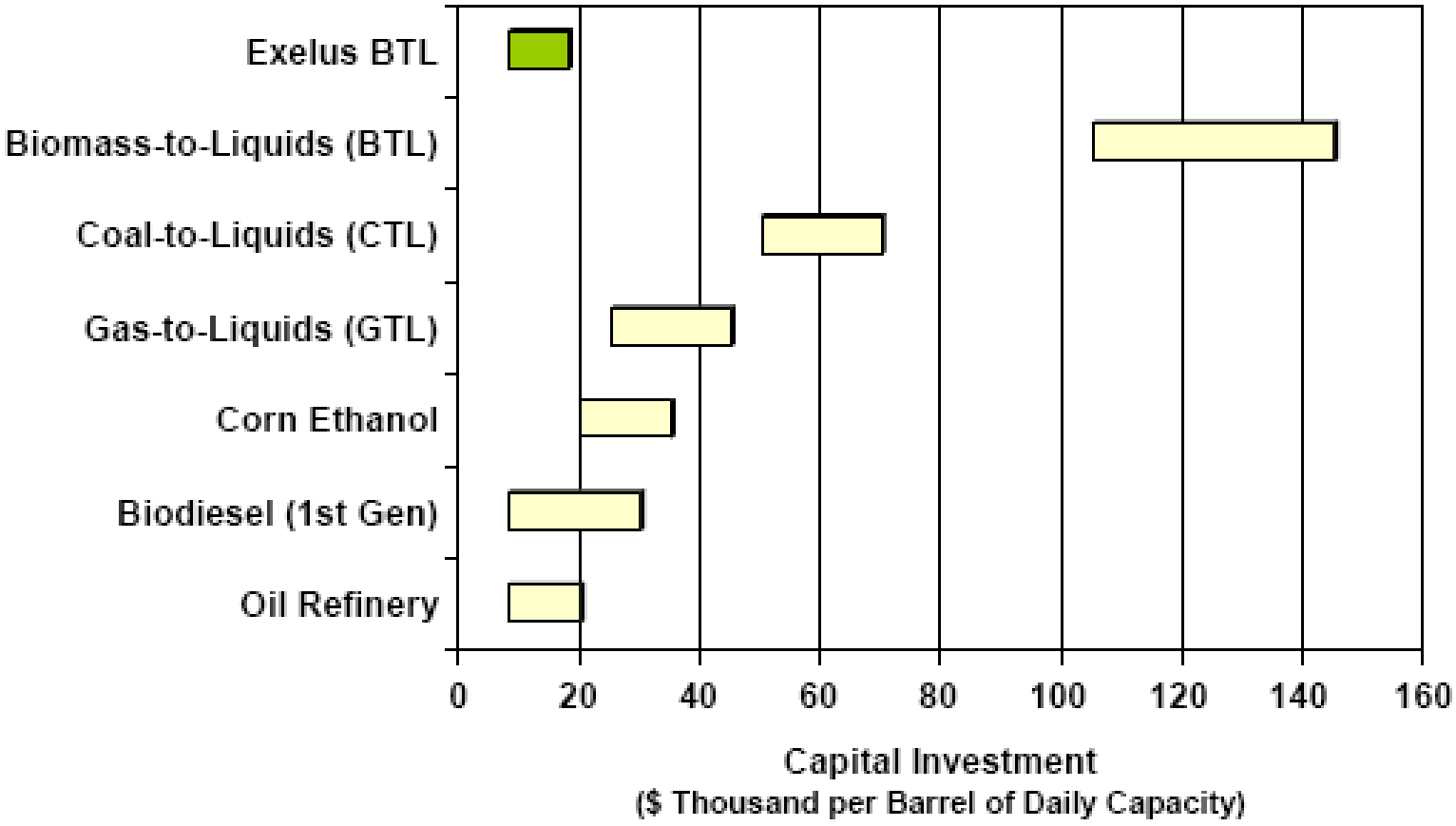
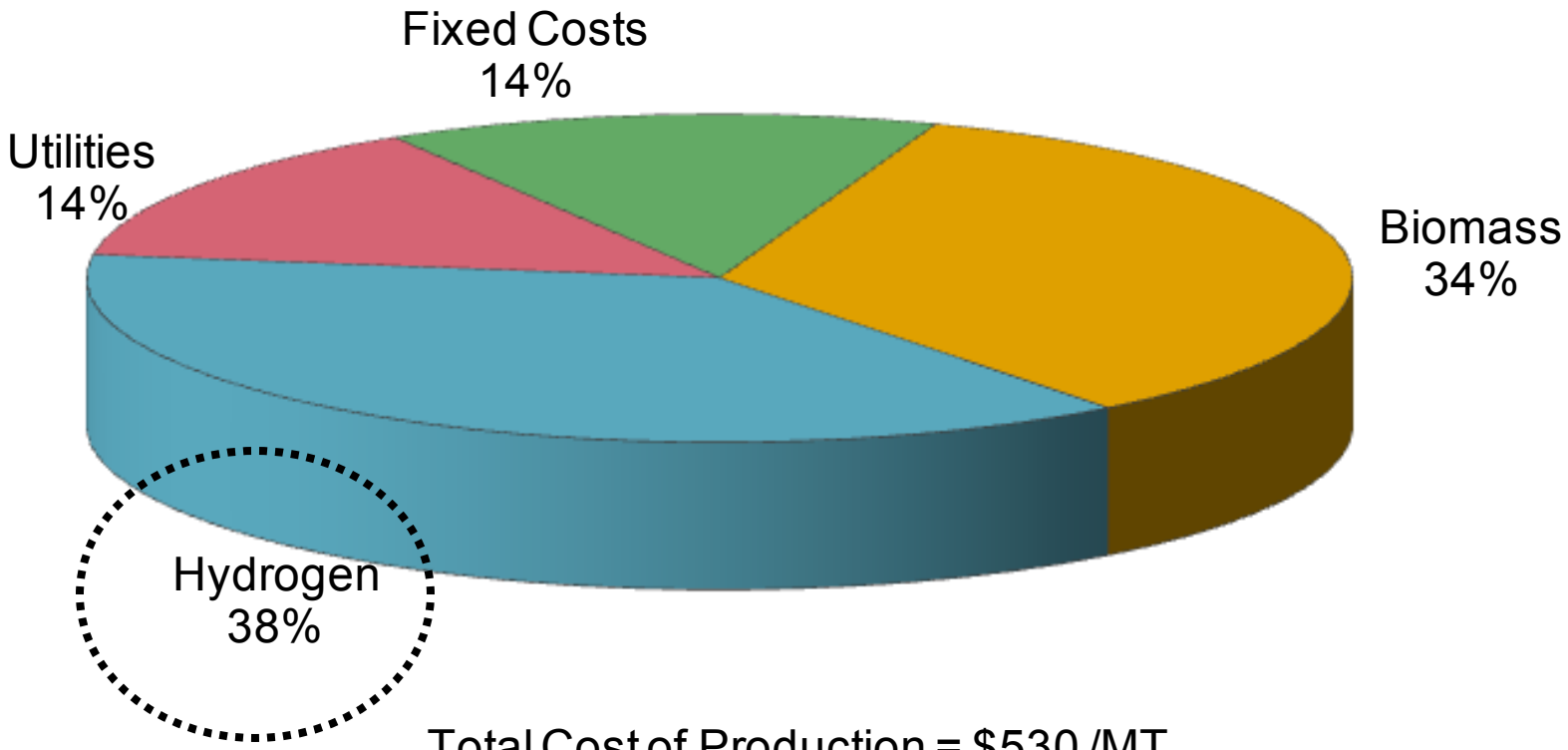
High Capital Costs



Variable Costs



Total Cost of Production = $530 /MT

Estimated Bio-Gasoline Cost = $2.00/gal

Assumes 75% biomass and hydrogen selectivity

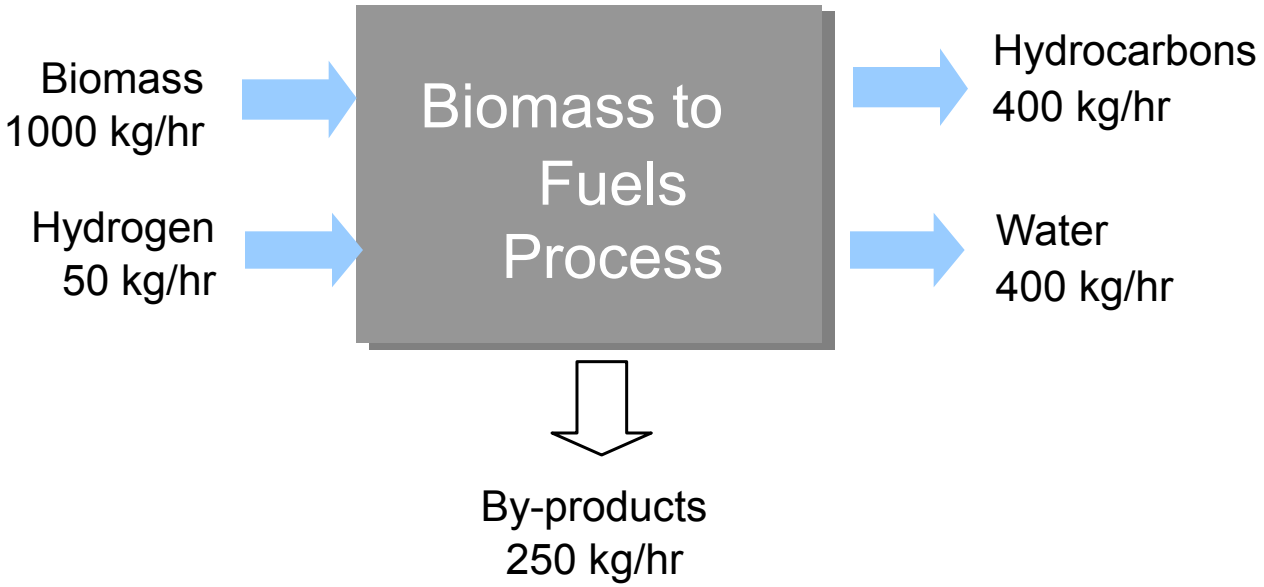
Future Work

Techno Economic Evaluation

Technology Validation

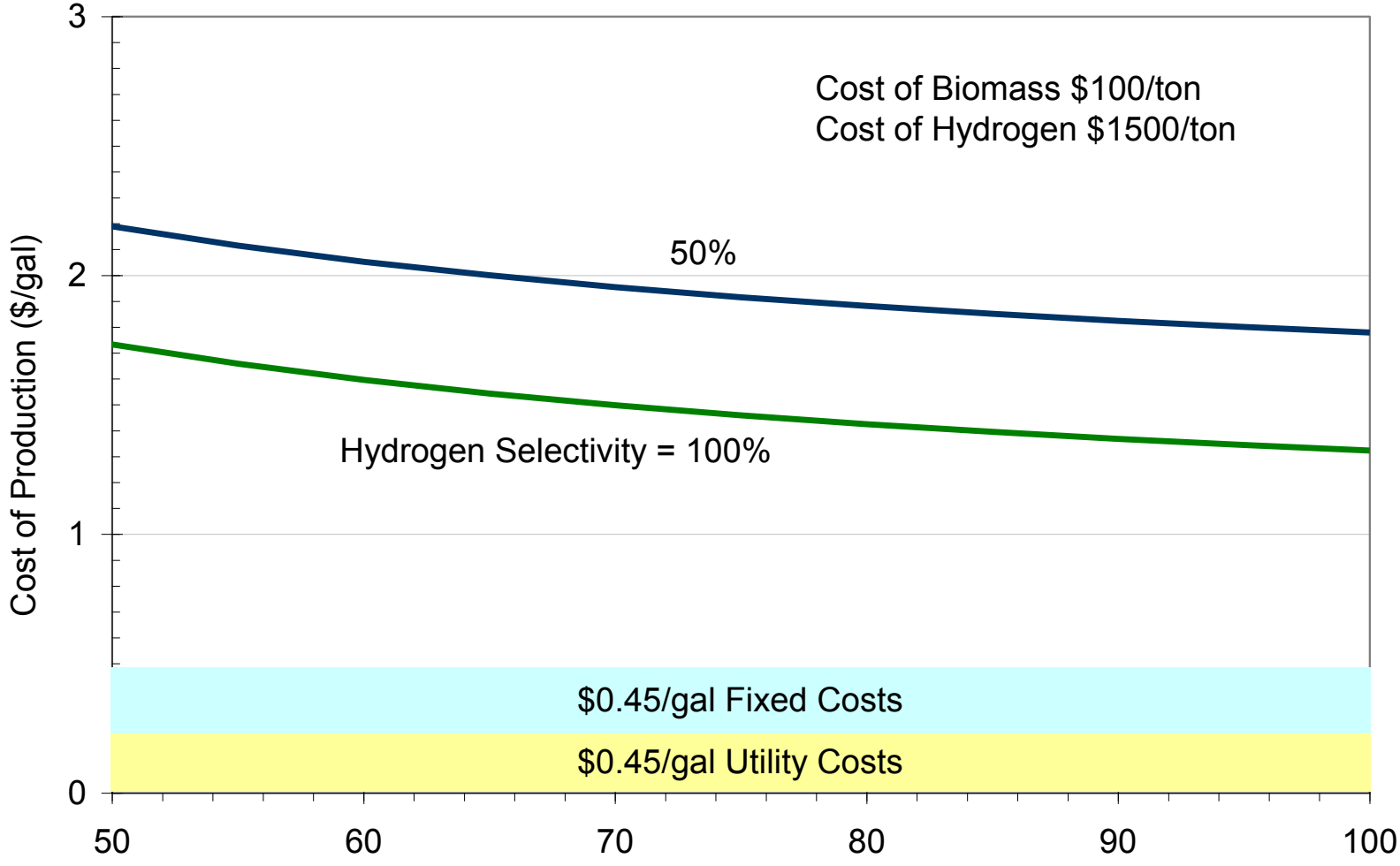
Developing Consortium Team

Mass Balance



Carbon Efficiency = 75%

Bio-Gasoline Cost of Production



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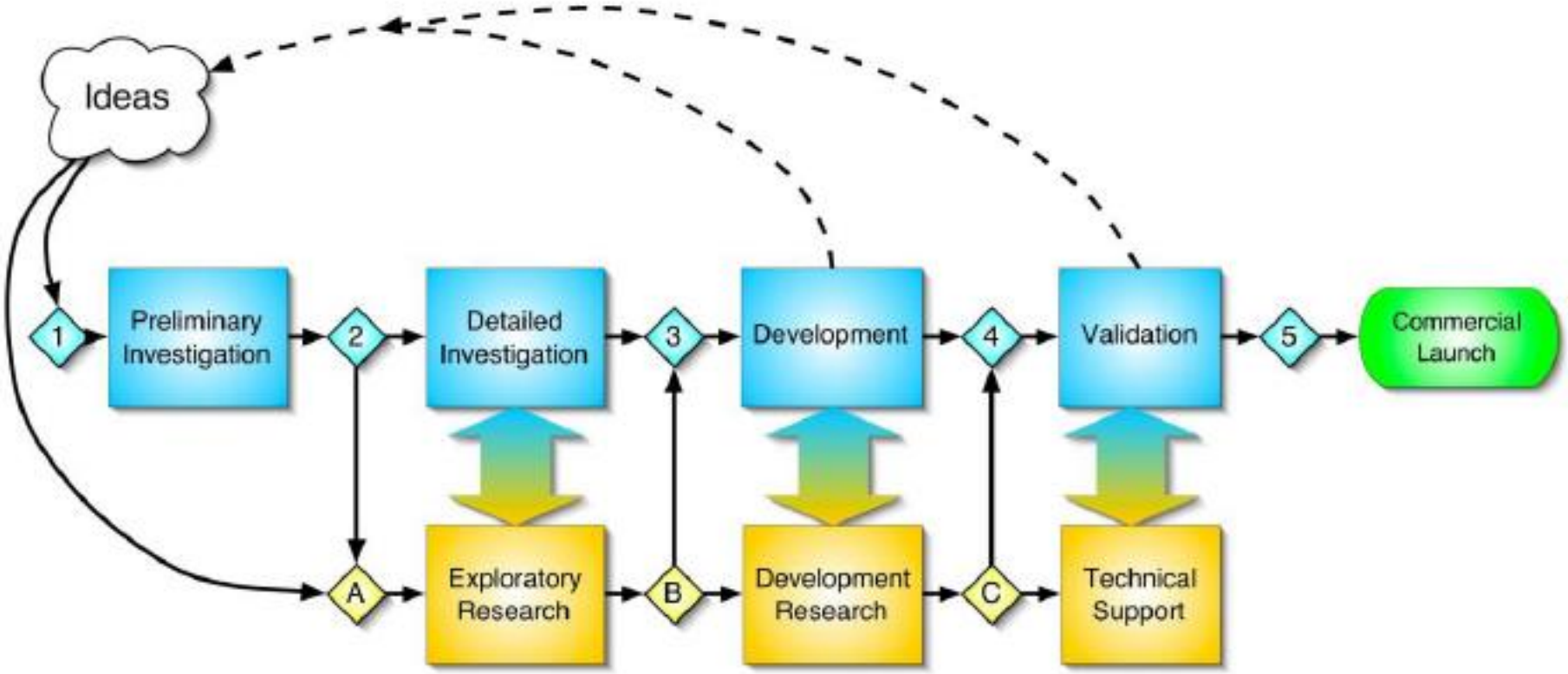
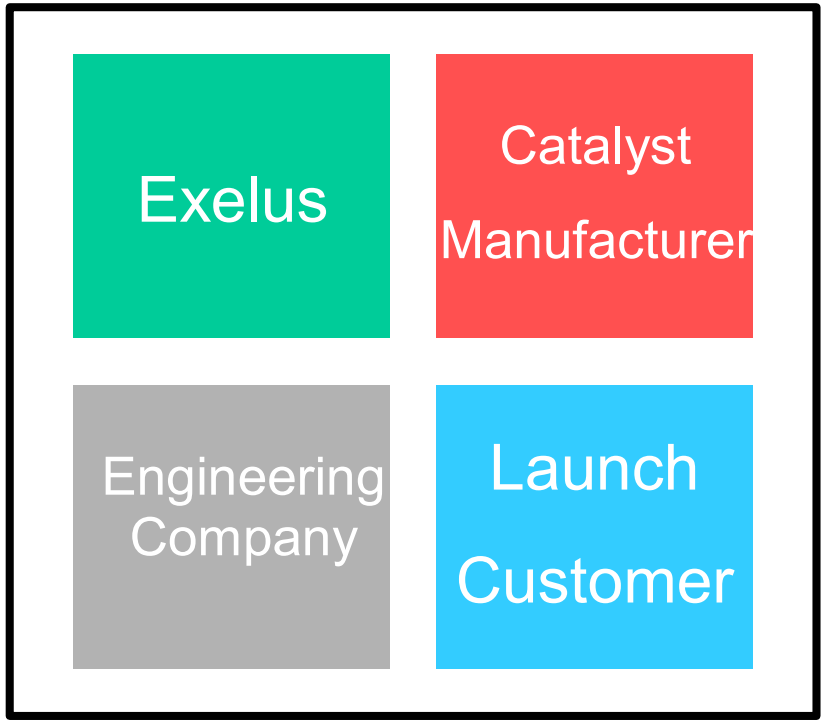
Technology Validation



Develop Consortium



Summary

- This project seeks to develop a break-through thermo-chemical process to convert cellulosic biomass into a high-octane gasoline blend-stock
- Exelus process replaces conventional high-temperature processes like gasification and pyrolysis with a series of mild, low-temperature reactions achieved using novel catalytic methods
- Selective conversion (>90%) of bio-mass to mixed alcohols has been demonstrated at mild conditions using “green” catalysts
- Future work will focus on techno-economic evaluation of this new B2G process

Questions