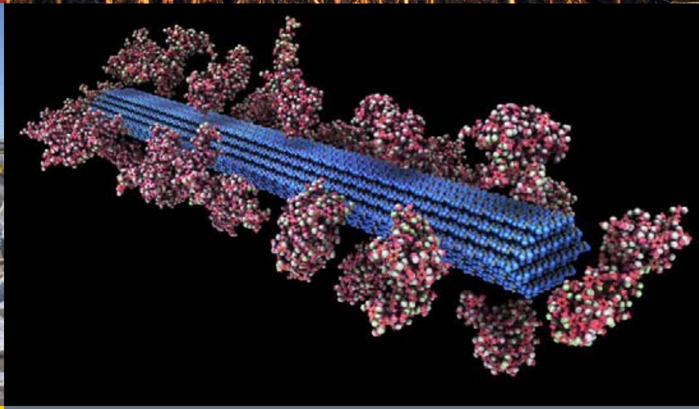
U.S. DEPARTMENT OF ENERGY
BIOENERGY TECHNOLOGIES OFFICE

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



Project Peer Review Overview Presentations

Conversion Technology Area

Kevin Craig
Program Manager

May 20, 2013

Outline

- Background
- Strategic Evolution
- Accomplishments
- Capabilities
- Goals and Objectives
- Approach
- Recent FOAs
- FY14 Direction
- Overview of Projects Being Reviewed

Bioenergy Technologies Office Overview (BETO)

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Mission: Through targeted RDD&D, enable sustainable, nationwide production of advanced biofuels that that will displace a share of petroleum-derived fuels, mitigate climate change, create American jobs, and increase U.S. energy security.

Research, Development, Demonstration, & Deployment

Feedstock Supply

Develop sustainable, secure, reliable, and affordable biomass feedstock supply.

Conversion R&D

Develop commercially viable technologies for converting biomass feedstocks into fungible, liquid transportation fuels, bioproducts and chemical intermediates

Demonstration & Deployment

Demonstrate and validate integrated technologies with successful construction and operation of cost-shared pilot, demonstration, and commercial scale facilities

Cross Cutting

Sustainability

Promote the positive economic, social, and environmental effects, while reducing potential negative impacts of biofuels

Strategic Analysis

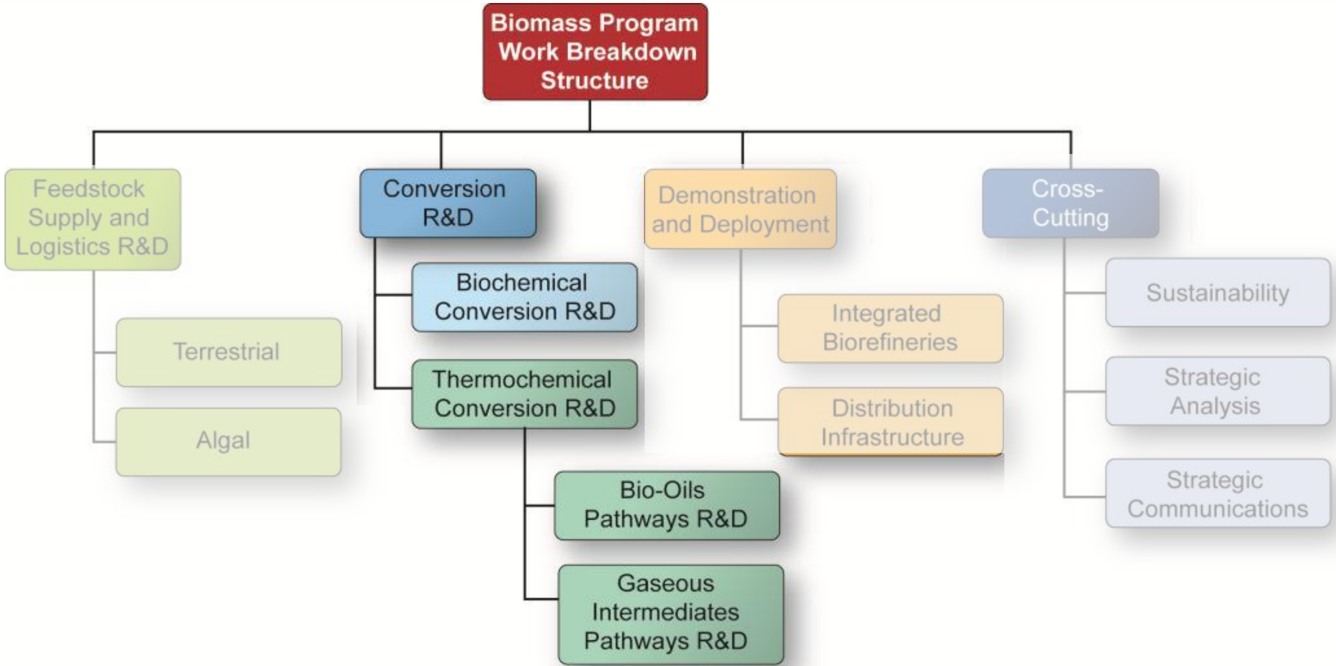
Provide context for decisions by establishing quantitative metrics, tracking progress toward goals, and informing portfolio planning and management

Introduction to Conversion R&D

Conversion R&D is focused on developing commercially viable technologies to convert terrestrial and algal feedstocks into liquid fuels, as well as bioproducts and biopower.

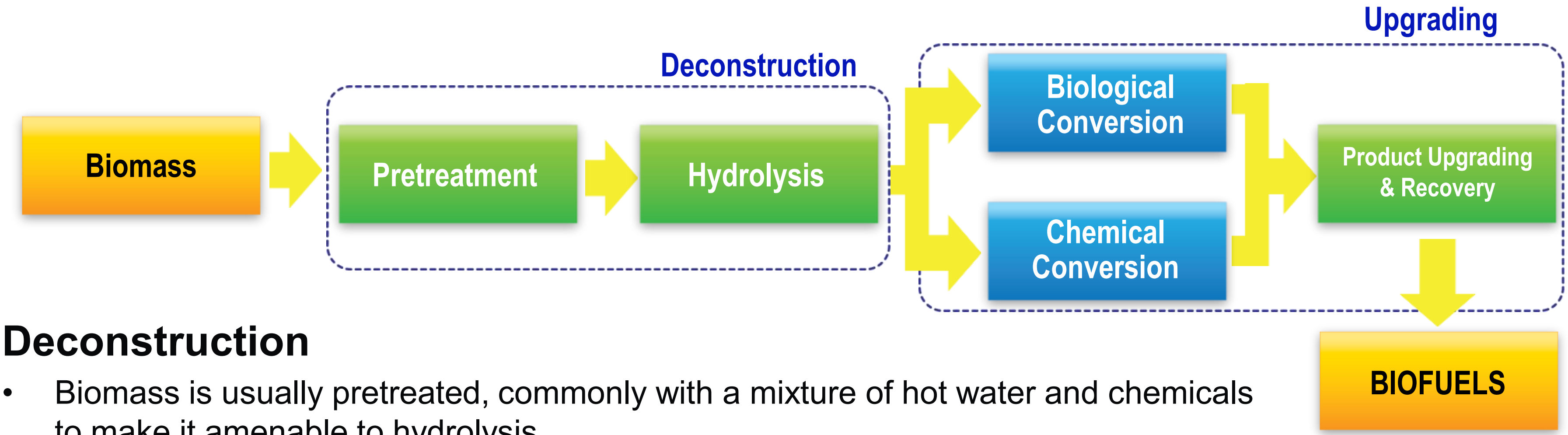
Biochemical Conversion R&D efforts focus on pathways for producing sugars and other carbohydrate intermediates, from biomass followed by conversion to finished fuels.

Thermochemical Conversion R&D is focused on pathways producing bio-oil and gaseous intermediates from biomass followed by upgrading to finished fuels.



Biochemical Conversion

R&D projects are improving the biochemical conversion of cellulosic biomass to biofuels and chemicals. These processing routes entail breaking down biomass to make the carbohydrates available for conversion into sugars that microorganisms and other catalysts can use to create biofuels and bioproducts.



Deconstruction

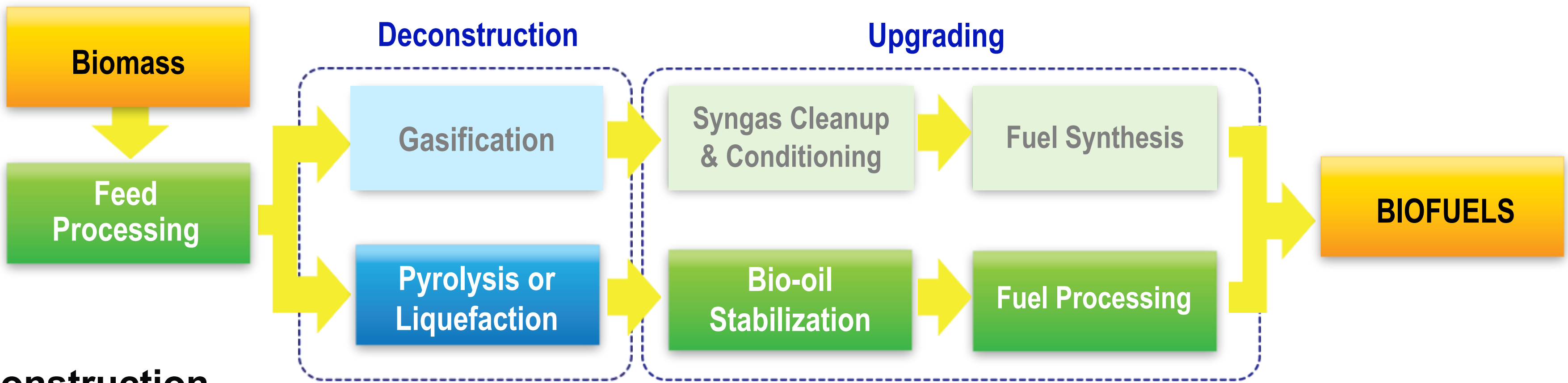
- Biomass is usually pretreated, commonly with a mixture of hot water and chemicals to make it amenable to hydrolysis.
- The pretreated biomass can be exposed to enzymes, which unlock and release (hydrolyze) the biomass sugars.
- Alternately, biomass can be completely deconstructed into sugar and carbohydrate streams using non-enzymatic processing technologies.

Upgrading

- The sugar-rich media is then fed to organisms, like yeast and E. Coli, which transform the sugars into biofuels and chemicals.
- Chemical catalysis can also be employed to transform the sugars into biofuels and chemicals.

Thermochemical Conversion

RD&D projects are improving the thermochemical conversion routes for cellulosic and algae biomass. These processing routes use heat and chemistry to convert biomass. Conversion technologies include both direct and indirect liquefaction routes followed by upgrading to finished fuels (gasoline, jet, or diesel). Off gases and other waste streams are captured for process heat and power or hydrogen generation.



Deconstruction

- Gasification efforts are being de-emphasized after 2012 demonstration on cellulosic ethanol.
- Pyrolysis or liquefaction processes convert biomass to condensable vapors, non-condensable gases, char, and coke. The condensable vapors are quenched, and two liquid phases are formed: a bio-oil phase and an aqueous phase.

Upgrading

- Synthesis gas is cleaned (inorganics and CO2 removal) and conditioned (tar reforming) and converted into biofuels and chemicals using catalysts.
- The bio-oil phase is upgraded through various hydroprocessing, separations, and/or fractionation steps to stabilize and remove oxygen from the bio-oil in order to produce an acceptable petroleum refinery feedstock or finished fuels

FY12 Key Accomplishment: Cellulosic Ethanol Validations

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

In September 2012, scientists at DOE's National Laboratories successfully demonstrated feedstock and conversion processes that reduced the cost of production of cellulosic ethanol.

- ~90% reduction in enzyme cost through development of new enzymes for biochemical processing ($3.45/gal to $0.36/gal)
- New microbes that can use more sugars (glucose, xylose, arabinose) - from ~50% to >95%
- Improved methane conversion in thermochemical processes - from 20% to 80%

Feedstock → Biochemical Conversion (Deconstruction and Fermentation) → Ethanol **=$2.15**

Feedstock: 2001 = $1.25/gal; 2012 = $0.83/gal ↓

Biochemical Conversion: 2001 = $6.02/gal; 2012 = $0.81/gal ↓

Ethanol: 2001 = $1.90/gal; 2012 = $0.51/gal ↓ (balance of plant)

Feedstock → Thermochemical Conversion (Gasification and Fuels Synthesis) → Ethanol **=$2.05**

Feedstock: 2007 = $1.40/gal; 2012 = $0.73/gal ↓

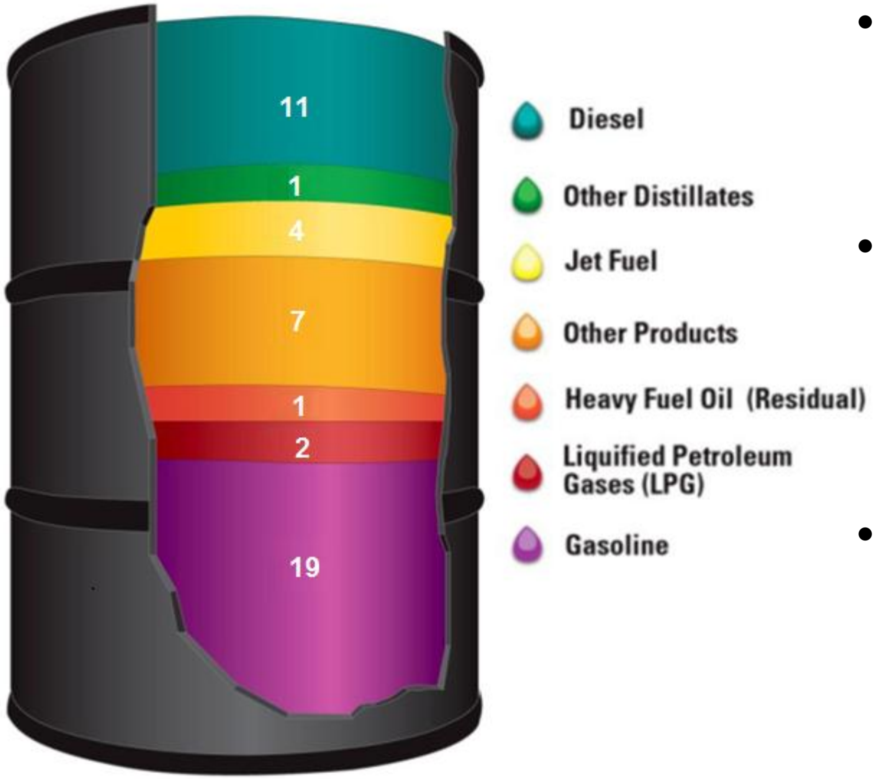
Thermochemical Conversion: 2007 = $3.38/gal; 2012 = $1.32/gal ↓

Ethanol: 2007 = -$0.03/gal; 2012 = $0.00/gal (balance of plant)

Current Strategic Focus: Replacing the Entire Barrel

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Products Made from a Barrel of Crude Oil (Gallons)
(2011)



In 2011 BETO re-examined its focus:

- Cellulosic ethanol only displaces gasoline fraction of a barrel of oil (about 40%).
- Reducing dependence on oil requires replacing diesel, jet, heavy distillates, and a range of other chemicals and products.
- Greater focus needed on RDD&D for a range of technologies to **produce hydrocarbon fuels and displace the entire barrel of petroleum**.

Source: Energy Information Administration, “Oil: Crude Oil and Petroleum Products Explained” and AEO2009, Updated July 2012, Reference Case.
*American Petroleum Institute.

Feedback from Peer Review 2011

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Biochemical

- Expand organism focus to consider consortia and other industrial relevant organisms
  - Increased the biological pathways considered
  - Process Integration/Synthetic Bio FOAs were unrestrictive and allowed for consortia and a wide range of organism development
- Expand focus to include diverse set of feedstocks
  - Process Integration FOA/Core R&D
- Increase focus on alterative intermediate streams
  - Lignin utilization
- Parallel conversion approaches (unit operations)
  - See newly expanded pathway approach.

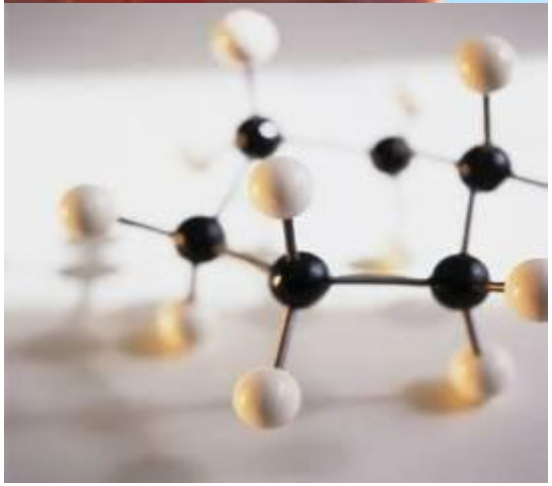
Thermochemical

- Require TEA's and LCA of all projects (including assumptions and uncertainties)
- Include by-products in design cases/TEAs/LCAs (i.e. chemicals, hydrogen, and bio-heat/power)
- Develop additional cost projection models for other pathways.
- Use Design Case cost projects as a "score card" for all projects to track their SOT and to make comparisons *(still a work in progress)*
- Enable hybrid and "new alternative" approaches
  - Lignin Utilization (w/Biochemical)
  - Algae and other HTL approaches
- Understand bio-oil quality and potential motor fuel end use and refinery integration

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Conversion Technologies for Advanced Biofuels (CTAB)

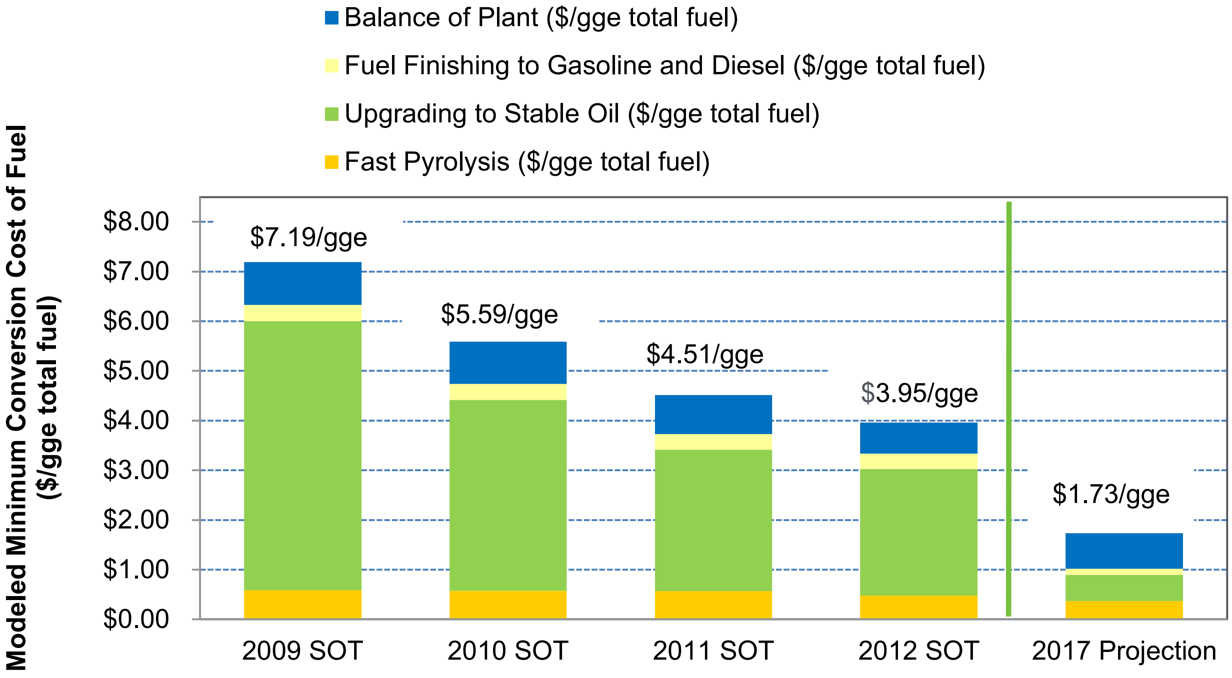
- Expand upon existing R&D roadmaps
  - *Update Breaking the Biological Barriers to Cellulosic Ethanol*
  - *Breaking the Chemical and Engineering Barriers to Lignocellulosic Biofuels)*
- **Areas of focus**: R&D Barriers and Activities - <u>dedicated focus to hydrocarbon biofuels</u>
- Gathered input from industry, national labs and academia
- Has already helped influence several programmatic decisions
- **Deliverable:** Roadmap for public dissemination which will guide BETO out-year R&D directions in 2013



By 2022, achieve the overall program performance cost goal of $3 per gallon of gasoline equivalent ($2011) based on data at the integrated pilot scale.

FY12 Key Accomplishment: TC 2012 SOT Conversion Cost

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



- $3.95/gge translates to ~$5.29/gge minimum gasoline/diesel selling price
- $1.73/gge translates to $2.59/gge minimum gasoline/diesel selling price.
- NOTE: Fast Pyrolysis Design Case is being updated by the end of FY13 and the program anticipates the cost projection will likely increase.
- New design cases are under development

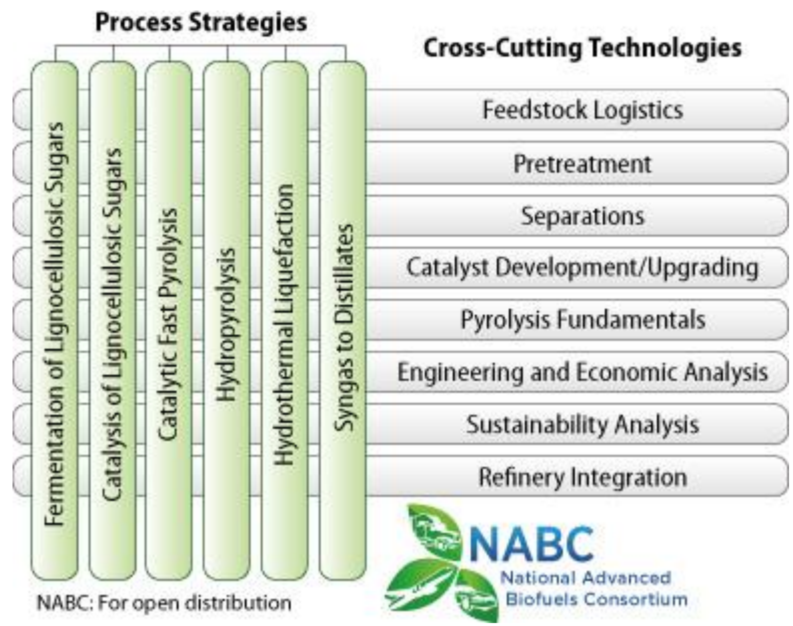
2011 Dollars	2009 SOT	2010 SOT	2011 SOT	2012 SOT	2017 Projection
Conversion Contribution ($/gal gasoline)	$7.55	$5.86	$4.73	$4.15	$1.83
Conversion Contribution ($/gal diesel)	$7.61	$5.92	$4.78	$4.20	$1.83
Conversion Contribution ($/GGE total fuel)	$7.19	$5.59	$4.51	$3.95	$1.73
Fast Pyrolysis ($/gal total fuel)	$0.62	$0.61	$0.60	$0.50	$0.39
Upgrading to Stable Oil ($/gal total fuel)	$5.70	$4.05	$3.00	$2.69	$0.55
Fuel Finishing to Gasoline and Diesel ($/gal total fuel)	$0.35	$0.34	$0.33	$0.33	$0.13
Balance of Plant ($/gal total fuel)	$0.91	$0.89	$0.83	$0.66	$0.75

Key Accomplishments: NABC

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

National Advanced Biofuels Consortia nearing successful completion

- Approximately $35 million in ARRA funding
- Included two research stages
  - Stage 1: Researched six process strategies for conversion of biomass feedstock to biofuels; utilized sustainability and technoeconomic analyses to downselect
  - Stage 2: Fall 2011
    - Selected two pilot-ready pathways: Fermentation of Lignocellulosic Sugars (FLS) and Catalysis of Lignocellulosic Sugars (CLS)
    - Selected 2 R&D pathways: Hydropyrolysis and Hydrothermal Liquefaction



Deliverables/Future Leverage:

- A technology package that includes a pilot ready process, a detailed design and engineering report, and a life-cycle analysis

Facility Capabilities: Biochemical R&D Validations

Advanced Biofuels Process Demonstration Unit (ABPDU) - LBNL

- Small scale demonstration unit for advanced biofuels production processes.
- 100-200lbs/day (biomass) and a capacity: 3-5 gallons/per day (fuel)
- Provides a unique capability around solvent pretreatment processing

Integrated Biorefinery Research Facility (IBRF) - NREL

- Establishes optimal and robust process conditions for production of hydrocarbon blendstocks from biochemical processes
- Provides industry partners with the opportunity to operate, test, and develop their own biorefining technology and equipment (27,000 ft2 of high bay space)
- Handles a wide range of biomass feedstocks and pretreatment processes

Process Development Units for Thermochemical R&D Validations

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Feedstock PDU - INL

- Modular and configurable: the right processing for the right blendstocks
- Production of feedstocks for $3/gal demonstration

Conversion PDUs – NREL and PNNL

- Establishing optimal and robust process conditions for the production of bio-oils and fuel blendstocks
- Production of fuel blendstocks for $3/gal 2017 and 2022 validations via various Bio-oil Pathways

Goals and Objectives: Biochemical Conversion R&D

Performance milestones in MYPP:

- By 2014, establish out-year cost goals and technical targets for biochemically derived hydrocarbon fuels based on techno-economic analysis for at least one technology pathway
- By 2017, validate the integrated production of a hydrocarbon fuel or fuel blend stock from cellulosic or algal biomass via at least one biological or biochemical route at bench-scale to measure progress against an interim modeled cost goal (nth plant, $2011), to be set in 2013

Long Term Goal:

- Develop technologies to convert cellulosic feedstocks to hydrocarbon fuels biochemically, achieving a modeled nth plan minimum fuel selling price of ~$5.00 gge in 2017 and ~$3.00 gge in 2022
- Develop multiple technology pathways, before selecting the most promising for use in the 2017 and 2022 validations.

Goals and Objectives: TC Bio-oil Pathways R&D

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Performance milestones in MYPP:

- By 2014, establish out-year conversion cost projections and technical targets for achieving a minimum fuel selling price of $3/GGE based on completed TEAs for two additional bio-oils pathways (i.e. *Ex situ* and *In situ* Catalytic Fast Pyrolysis).
- By 2015, evaluate bench scale, semi-integrated pyrolysis or liquefaction conversion and upgrading processes on formatted biomass to produce gasoline and diesel fuels. This data informs a decision on which bio-oil pathway will be selected for pilot-scale operation to demonstrate the 2017 design case projections for a minimum fuel selling price of $3/GGE.
- By 2017, demonstrate integrated pilot-scale operations on formatted biomass using pyrolysis or liquefaction conversion with upgrading to produce gasoline, diesel, or jet finished fuels to meet the 2017 design case projections for a minimum fuel selling price of $3/GGE.

Long Term Goal:

- Continue to develop and demonstrate new thermochemical bio-oil R&D pathway technologies to convert biomass to hydrocarbon fuels, achieving an nth plant modeled minimum fuel selling price of $3/GGE by 2022.

Goals and Objectives: TC Gaseous Intermediates R&D

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Performance milestones in MYPP:

- By EOY 2014, establish out-year cost goals and technical targets, based on completed techno-economic analysis, for at least one gaseous intermediate conversion to hydrocarbon fuels pathway.
- By 2022, validate integrated conversion process for biomass to renewable gasoline or diesel via conversion of gaseous intermediates at a scale sufficient for transfer to demo scale operations.

Long Term Goal:

- By 2022, achieve the overall Office performance cost goal of $3/GGE ($2011) via catalytic upgrading of biomass-derived gaseous intermediates to gasoline and diesel hydrocarbons.

[1] Based on Target Pathways Milestone Report, OCT12. Updates pending refinement of techno-economic analysis in 2014

Research Approach
Technology Pathways Development

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Design Cases are under development, based on:

- Feasibility of achieving programmatic cost goal of $3/gal
- Near/Mid/Long-term techno-economic potential
- Potential national impact
- Feedstock availability/flexibility
- Data availability across the full pathway

Technology Area	Design Cases by Pathway
Biochemical	Biological conversion of sugars[1]
	Chemical conversion of sugars[1]
Thermochemical Bio-Oils	EXISTING: Conventional Fast Pyrolysis and Upgrading (being updated)
	Catalytic Fast Pyrolysis (both *Ex Situ* and *In Situ* cases)
	Whole Algae Hydrothermal Liquefaction and Upgrading[2]
	Algal Oil Upgrading[2]
Thermochemical Gasification	Syngas Upgrading to Mixed Alcohols to Naptha Hydrocarbons

[1]Denotes that sugars actually refers to sugars or other lignocellulosic derivatives such as carbohydrate derivatives and lignin

[2]Denotes that these pathways are being examined in conjunction with the Algae Technology Area

Research Approach: Biochemical Pathways

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

<table>
<tr><th>Pathway</th><th>Description</th><th>Key Challenges & Barriers</th></tr>
<tr><td>Biological conversion of sugars*</td><td>Production of sugars or biomass via enzymatic or non-enzymatic routes and subsequent biological processing to yield hydrocarbon fuel precursors (e.g. fatty acids, isoprenoids, etc.)</td><td rowspan="3">• Biomass variability
• Biomass recalcitrance
• Biomass fractionation
• Lower costs/improve quality of intermediates
• Pretreatment processing and costs
• Cellulase enzyme production, loading and costs
• Enable high performance separations technologies
• Improve catalyst performance – cleanup/conditioning & fuel synthesis
• Biochemical conversion process integration
• Biochemical/thermochemical interface
• Maximize carbon utilization
• Optimize reactor performance</td></tr>
<tr><td>Chemical conversion of sugars*</td><td>Production of sugars or biomass carbohydrate derivates via enzymatic or non-enzymatic routes, and subsequent upgrading of the product stream through catalysis to yield a mix of hydrocarbons suitable for blending.</td></tr>
<tr><td>Catalytic upgrading of alcohols</td><td>Production of sugars via enzymatic hydrolysis followed by fermentation to ethanol, and catalytic upgrading of ethanol to paraffins.</td></tr>
</table>

The CTAB workshop identified barriers that apply to these pathways

***Denotes that sugars actually refers to sugars or other lignocellulosic derivatives such as carbohydrate derivatives and lignin**

Research Approach: TC Bio-oil Pathways

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Pathway	Description	Key Challenges & Barriers
Fast Pyrolysis (FP) with Liquid Phase Upgrading	FP followed by a separate liquid phase upgrading step, then multi-stage hydrotreating	• Feeding wet and dry biomass • Catalyst and catalytic process comprehension • Hydroprocessing and hydrogen considerations • Separation systems and selective fractionation • Sensors and controls • Liquefaction of biomass and bio-oil stabilization • Fuel synthesis and upgrading • Utilizing Organics in Waste Streams (Aqueous Phase and Off Gases) • Bio-oil pathway process integration • Refinery Integration
FP with Ex-Situ Vapor Phase Upgrading	FP followed by a separate vapor phase upgrading step, then one or two stages of hydrotreating	
FP with In-Situ Vapor Phase Upgrading	FP in the same reactor as upgrading catalyst, followed by one or two stages of hydrotreating	
Hydrothermal Liquefaction (HTL) or Solvent Liquefaction (SL)	Direct liquefaction in water (HTL) or solvent medium (SL), followed by catalytic upgrading. Used with high moisture feedstocks, such as algae	
Hydropyrolysis	FP in the presence of hydrogen and catalysts, followed by one stage of hydrotreating	

The CTAB workshop identified barriers that apply to these pathways

Research Approach: TC Gaseous Intermediates Pathways

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Pathway	Description	Key Challenges & Barriers
Syngas Upgrading to Hydrocarbon Fuels Technology Pathway	Upgrading of biomass derived synthesis gas ('syngas') to hydrocarbon fuels. While this specific discussion focuses on the conversion of syngas via a methanol intermediate to hydrocarbon blendstocks, there are a number of alternative conversion routes for production of hydrocarbons through a wide array of intermediates from syngas.	• Feeding wet and dry biomass • High-temperature gas production from biomass • Low-temperature production of gaseous intermediates • Gas cleanup and conditioning • Validation of syngas quality • Liquefaction of biomass and bio-oil stabilization • Fuel synthesis and upgrading • Sensors and controls • Gaseous intermediates process integration

The CTAB workshop identified barriers that apply to these pathways

Recent FOAs and FY14 Direction

Recent FOAs (projects selected from these FOAs will be presenting during peer review sessions)

- Biochemical - Process integration
- Biochemical - Synthetic biology
- USDA-DOE Joint Solicitation
- Catalytic Upgrading of TC Intermediates to Hydrocarbons
- Thermochemical - Bio-oil Stabilization and Commoditization
- Thermochemical - CHASE Bio-oil Pathways (no selections, yet)

FY 2014 Budget Request & Potential New FOAs & Initiatives

- Advancing Technologies for Bioconversion Efficiency/Carbohydrate Upgrading FOA
- Carbon Fibers Initiative
- Waste to Energy
- Refinery Integration

FY11 Biochemical FOA: Process Integration

Goal of program effort: Enable chemical and/or biological process conversion improvements and integration with feedstock handling and processing with pretreatment and hydrolysis (saccharification) technologies

Barriers were addressed by two topic areas:

- **Topic Area 1 –** Process improvements to a single unit operation to be incorporated into an integrated system.
- **Topic Area 2 –** Process improvements to 2 or more unit operations in an integrated system.

Selections include the following:

Topic Area 1:

- Genomatica
- Michigan Biotechnology Institute (MBI)
- Texas Engineering Experiment Station (TEES)

Topic Area 2:

- Virent
- virdia

- Diverse set of feedstocks
- Diverse unit operations
- TRLs: 3-6
- Products include:
  - BDO
  - Gasoline, Jet, Diesel
  - Carbohydrates (sugar, etc)

FY12 Biochemical FOA: Synthetic Biology

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Goal of program effort: Bring to bear the power of synthetic biology on key barriers within biochemical routes to fuels and chemicals

Barriers were addressed by two topic areas:

- **Topic Area 1- Intermediate Production:** Innovative synthetic biological approaches to the cost-effective fractionation of lignocellulosic biomass
- **Topic Area 2 – Intermediate Transformations:** Innovative synthetic biological approaches to the cost-effective and high yield conversion of processable component fractions into advanced biofuels and high-energy impact bioproducts. (*Even synthesis gas was included)*

Selections include the following

- J. Craig Venter Institute
- Novozymes, Inc.
- Pacific Northwest National Laboratory
- Texas AgriLife
- Lygos, Inc.

- Diverse set of feedstocks
- Intermediates include:
  - Carbohydrates (sugar, etc)
  - Lignin
  - TRLs: 2-4

J. Craig Venter Institute | novozymes Rethink Tomorrow | Pacific Northwest National Laboratory | Texas A&M AgriLife Extension | LYGOS

USDA-DOE Joint Solicitation - BRDI

The Biomass Research and Development Initiative (BRDI) is a collaboration between DOE and USDA as directed under various statutory authorities, primarily the Food, Conservation, and Energy Act of 2008 (The Farm Bill) and the Energy Policy Act of 2005.

The technical areas that BRDI is legislatively directed to address are:

- **Topic Area 1** – Feedstock Development
- **Topic Area 2** – Biofuels and Bioproducts Development
- **Topic Area 3** – Biofuels Development Analysis

On an annual basis, USDA and DOE collaboratively review and assess proposals, and then each agency separately funds and manages the selected awards.

Projects from 2009 –present that DOE has funded under BRDI are:

- 2009: Exelus (will be reviewed in Bio-oils platform)
- 2010: Metabolix (will be reviewed in Feedstock platform)
- 2011: Iowa State/Catchlight Energy (will be reviewed in TC Bio-oils Peer Review breakout session)
- 2012: Not announced yet

Exelus | Metabolix Bio-industrial Evolution™ | Iowa State University

FY11 TC FOA: Catalytic Upgrading of TC Intermediates to Hydrocarbons

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Goal of program effort: develop technologies in the area of thermochemical conversion of biomass to liquid hydrocarbon ("drop-in") fuels and chemical products

Projects were asked to:

- Develop technology and processes that yield a finished fuel (blendstock) infrastructure-ready hydrocarbon, and/or biofuel-enabling chemical product.
- Use at least three different biomass feedstocks: woody biomass, corn stover, and any other renewable lignocellulosic or algal material
- Accumulate 2000 hours of integrated operations

Selections include the following

- LanzaTech, Inc.
- Research Triangle Institute
- Virent Energy Systems, Inc.

DE-FOA-0000467

- Federal Funds: $11,997,665
- TRL: 4-6

LanzaTech | RTI International | VIRENT

FY12 TC FOA: Bio-Oil Stabilization and Commoditization (BOSC)

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Goal of program effort: To produce a bio-oil feedstock suitable for use within a petroleum refinery and leverage its existing capital for further processing to final fuels

Barriers were addressed by two topic areas:

- **Topic Area 1 –** Identify and perform necessary R&D for making bio-oil feedstock acceptable in a petroleum refinery and engage a refinery partner
- **Topic Area 2 –** Partner with petroleum refiner at the time of application and execute a coordinated R&D work plan for making bio-oil feedstock acceptable for further processing to transportation fuels and other co-products

Selections include the following

- Southern Research Institute [1]
- Stevens Institute of Technology [1]
- Idaho National Laboratory [1]
- Sapphire Energy [1]
- Iowa State University [1]
- University of Georgia [1]
- Gas Technology Institute [2]
- Pacific Northwest National Laboratory [2]

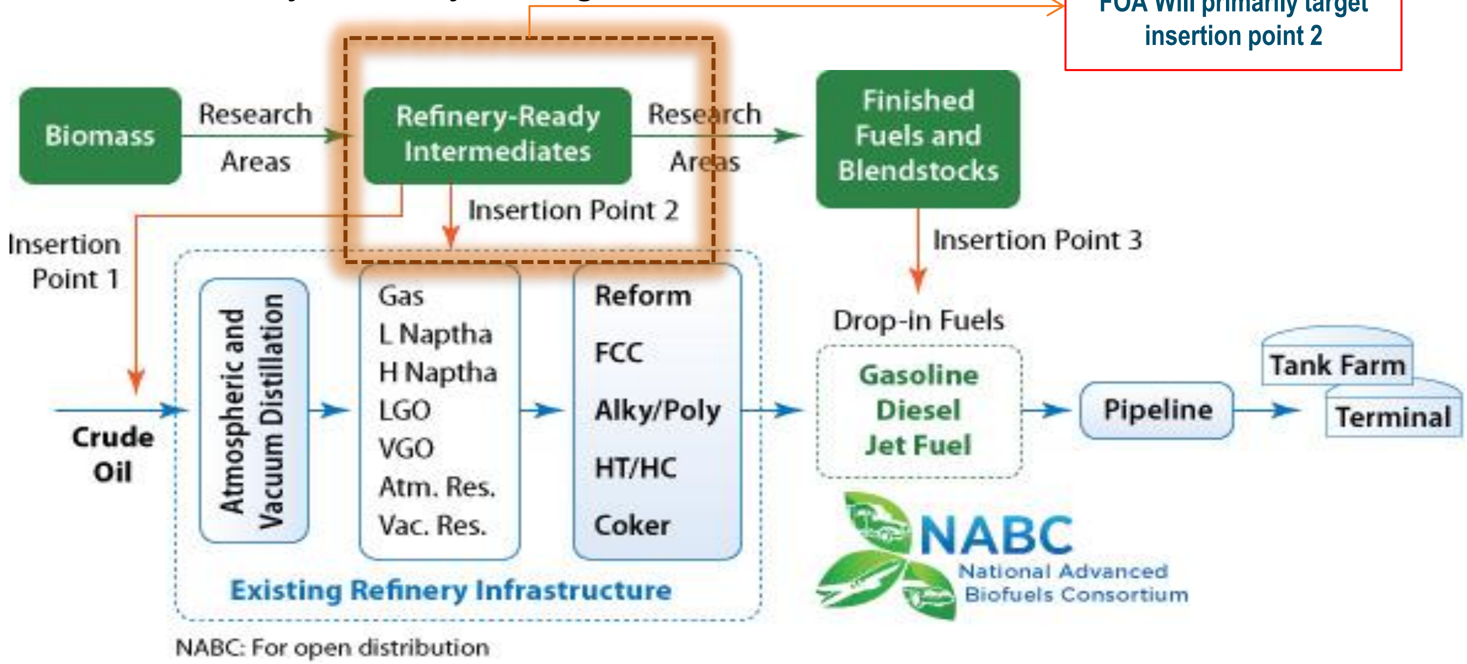
DE-FOA-0000686

- Federal Funds: $11,133,654
- TRL (TA1): 2-3
- TRL (TA2): 4-6

FY12 BOSC FOA: Integrating Bio-Oils in a Refinery

Programmatic Context:

- Peer Review 2011 – Need to process bio-oil in a petroleum refinery
- NABC – Insertion point 1 is not likely, a combination of 2 & 3 is most likely
- Core R&D – Insertion point 3 is possible, but may be costly
- CTAB Workshop, December 2011 barriers:
  - What's the market size for utilizing bio-oils in a refinery?
  - What are the minimum requirements for bio-oils for integration into a refinery?
  - Is the refinery industry willing to collaborate?



FY13 TC FOA: Carbon, Hydrogen, & Separation Efficiencies in Bio-Oil Pathways

Goal of program effort: To address R&D challenges that were identified at the "Conversion Technologies for Advanced Biofuels" workshop, specifically in Carbon, Hydrogen, and Separations Efficiencies (CHASE) for Bio-oil Pathways.

Three Technical Barrier Areas were identified:

- **Carbon Efficiency** – Typically only the organic phase is processed in subsequent upgrading steps, leaving behind valuable carbon-containing material in the aqueous phase.
- **Hydrogen Efficiency** – Currently, many systems use steam reforming of non-renewable natural gas to generate hydrogen.
- **Separations Efficiency** - The ability to remove destabilizing components from bio-oils is crucial to achieving improved processes for bio-products production.

Selections pending

- Announcements anticipated Summer 2013

DE-FOA-0000812

- Federal Funds: up to $12,000,000
- Starting TRL: 2-3

FY14 Budget: Biochemical and Thermochemical R&D

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

- Current budgets for both Technology Areas maintain their core laboratory competency
- New FY 2014 initiatives are CF, WTE, and the cross-cutting Incubator Program

(Dollars in Thousands)	FY 2012 Current	FY 2013	FY 2014 Request
Biochemical Conversion	53,500	37,075	77,000
Carbon Fiber Initiative	—	—	20,000
Waste-to-Energy	—	—	5,000
Incubator Program	—	—	10,000

(Dollars in Thousands)	FY 2012 Current	FY 2013	FY 2014 Request
Thermochemical Conversion	52,500	43,982	64,000
Incubator Program	—	—	10,000

Future R&D: Biochemical and Thermochemical Conversion

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Conversion activities for FY 2014 include continued efforts in both core and competitive R&D, and will focus on the following activities:

FY 2014 Biochemical Conversion R&D Activities

- Activities will focus on optimizing biomass deconstruction technologies, reducing the cost of intermediates, and exploring innovative upgrading technologies for maximum carbon utilization.
- Funds are increased to initiate three new programs beyond fuels to include use of wastes to produce energy and products, lignin and cellulosic sugar utilization to produce carbon fibers, and a new incubator program.

FY 2014 Thermochemical Conversion R&D Activities

- Focus indirect liquefaction R&D efforts on gaseous intermediates and mixed oxygenate upgrading to produce gasoline, distillate, and jet range hydrocarbons from biomass in support of the programmatic goal of $3/gge by 2022.
- Develop techno-economic analysis and associated design cases that include cost projections and technical targets for direct and indirect liquefaction pathways to make gasoline, diesel, or jet fuels at $3/gge by 2022.
- Initiate new Incubator Program to enable small business innovations.

FY 2014 Biochemical: Potential FOA

Advancing Technologies for Bioconversion Efficiency

- Follow up to the FY 2011 Process Integration FOA to further advance R&D on integrated process steps to impact overall process economics.
- Will address high-priority cost components, as described in BETO's Multi-Year Program Plan and Conversion Technologies for Advanced Biofuels Roadmapping Workshop, based on the new techno-economic analyses completed in FY 2012 and FY 2013.

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Potential Carbon Fiber Initiative

- BETO will fund this Clean-Energy Manufacturing Initiative in FY 2014 by initiating work under a competitive FOA and directly engaging with national laboratories. Activities will include the following:
- Research and scale-up of technologies for lignin deconstruction, separation, and upgrading to new carbon fibers with better performance properties.
- Research and scale-up of technologies for the clean-up and conversion of cellulosic sugars to acrylonitrile and other carbon fiber precursors using advanced microbial and chemical catalysts.
- Early stage evaluation of the suitability of the biomass-derived precursors for advanced carbon fiber manufacturing through collaboration with AMO.
- Process simulations and modeling for techno-economic and life-cycle analyses.

- Carbon fiber for vehicles
  - $5/lb
  - Strength > 250KSI
  - Modulus > 25 MSI
  - Strain to failure > 1%
- Opens opportunities for other applications

Potential Waste-to-Energy (WTE) Initiative

Proposed Initial WTE efforts:

- Productivity enhancements/cost reductions in the process unit operations associated with anaerobic digestion technology applications:
  - Feedstock pre-processing/pretreatment
  - Biogas cleanup/upgrading and methane splitting
  - Effluent refining
  - Digestate stabilization
  - Water Recycling
  - Process optimization
  - Process control
- Anaerobic consortia strain identification/culture techniques
- Transformation systems
- Metagenomic Analyses
- Inventory of Metabolic Pathways
- Development of optimized inocula
- Manufacturing technologies for customized inocula production

New technologies are synergistic with waste biomass utilization:

- Enhanced Anaerobic Digestion
- Microbial Fuel Cells
- Microbial Electrolysis Cells
- Bioelectrochemical Systems

FY 2014 Thermochemical FOAs

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Bio-Oil FOA: R&D on Petroleum Refinery Integration of Bio-Oils

- Follow up to the FY 2012 Bio-Oil Stabilization and Commoditization FOA to further advance work on producing acceptable bio-oil intermediates for petroleum refineries to leverage their existing capital to produce finished fuels.

Syngas FOA: R&D on Syngas to Hydrocarbon Fuels and Fuel Components

- Develop indirect liquefaction catalysts and processes to produce hydrocarbon fuels and fuel components from biomass. Activities will include process intensification, as well as yield and efficiency improvements for gasification processes and downstream liquefaction processes. R&D aims to understand/model—to the molecular level—catalysts' activity mechanisms and develop analytic tools for in situ characterization.

Incubator Program

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

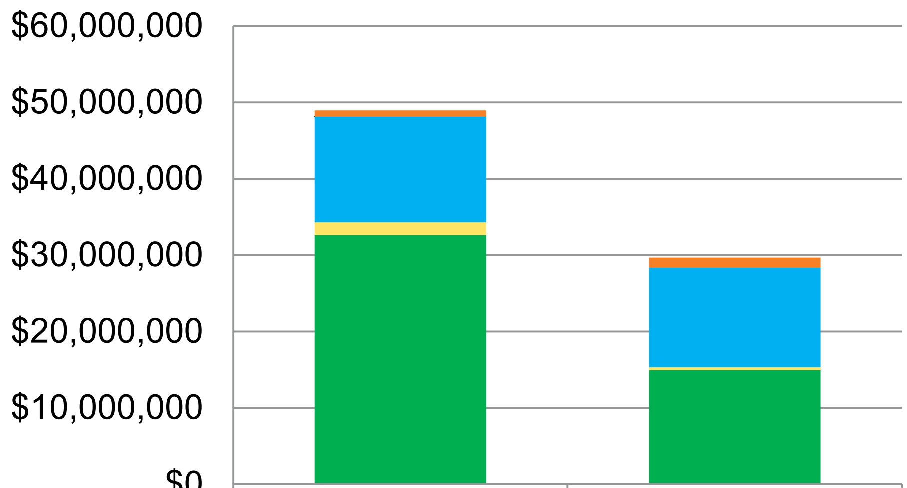
Vision for the Program (from A/S Dr. David Danielson)

- An "on-ramp" for new technologies/pathways/approaches to the complement existing roadmap (the Multi-Year Program Plan)
- Language in FY2014 Budget request: "targeting off-roadmap innovation"
- A separate annual FOA that will explicitly focus on new technologies/pathways/approaches that are not supported in a meaningful way the in current MYPP
- FOA should be written as open as possible
- A/S has given each program within EERE flexibility to design and execute the Incubator Program.
- Opening parameters: ~5-10% of total budget with ~1-3 yr "seedling" awards between $1-$3M

The details are still being worked out

Budget: Biochemical R&D (numbers after rescission)

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



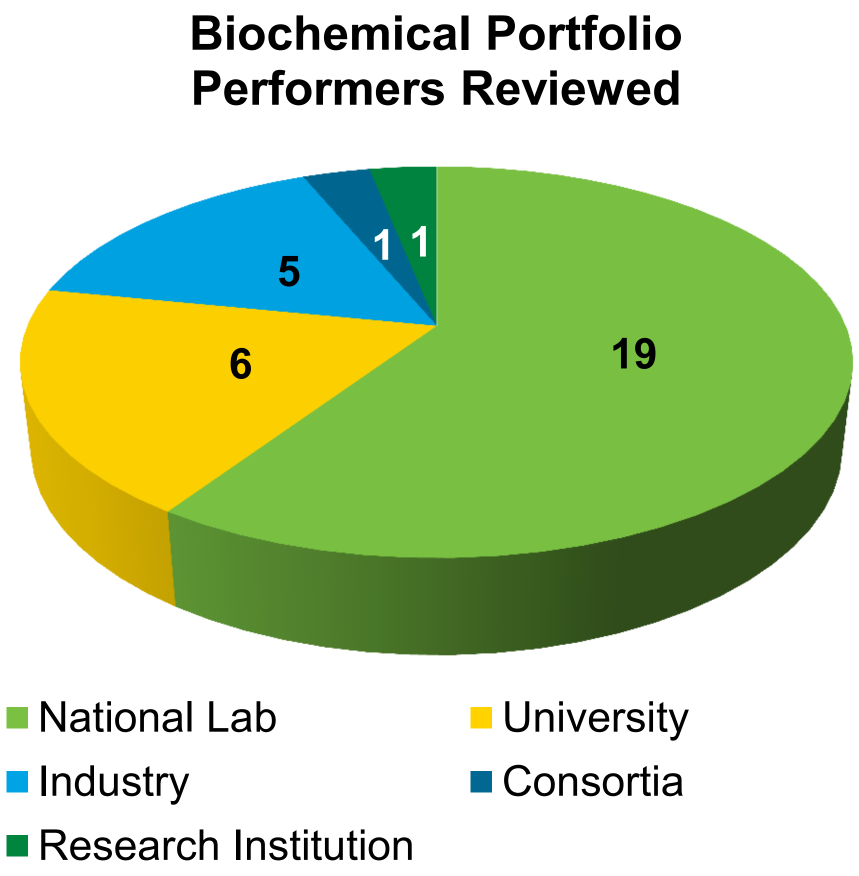
	FY 2012	FY 2013
Administrative	$837,300	$1,340,864
International	$30,000	
Competitivey Selected Projects	$13,832,600	$13,052,705
Analysis	$1,658,750	$385,000
Lab Core R&D	$32,604,373	$14,910,627

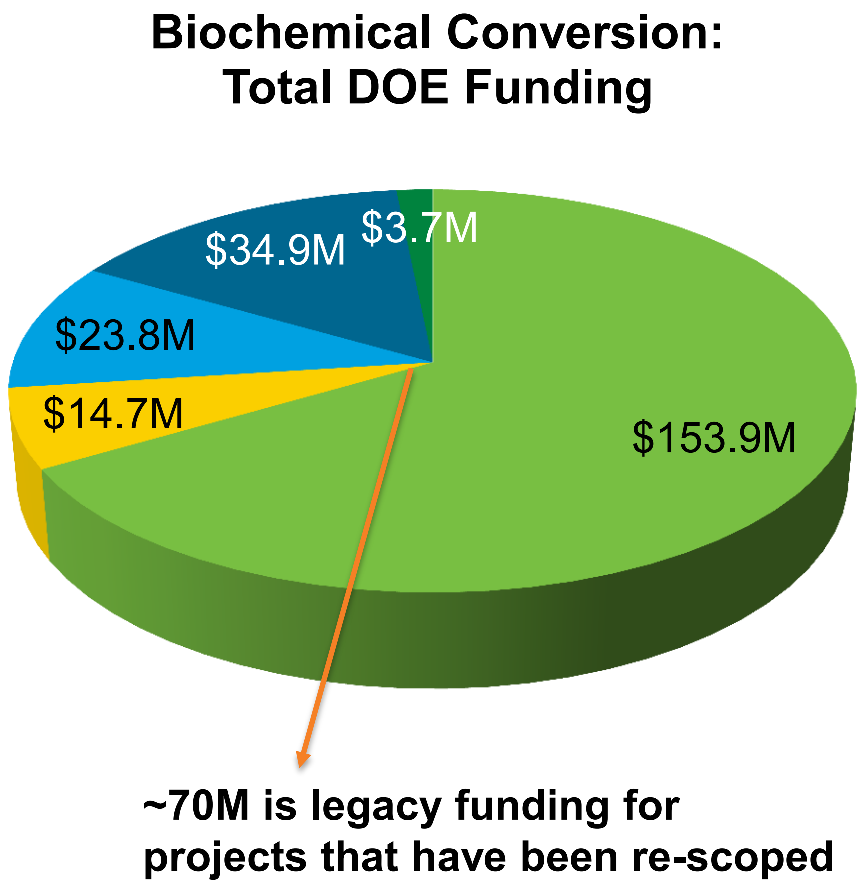
- Overall, BC funding decreased from ~$50m to $30m, as cellulosic ethanol R&D was de-emphasized and the portfolio was shifted to include hydrocarbon fuels – at a smaller scale of R&D.
- Lab Core R&D decreased from FY12-13, as FY12 funding was at its peaked for the cellulosic ethanol integrated pilot validation tasks.
- ~ $10m in FY12/13 was directed at new projects from Synthetic Biology FOA.

Biochemical Conversion Project Portfolio

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

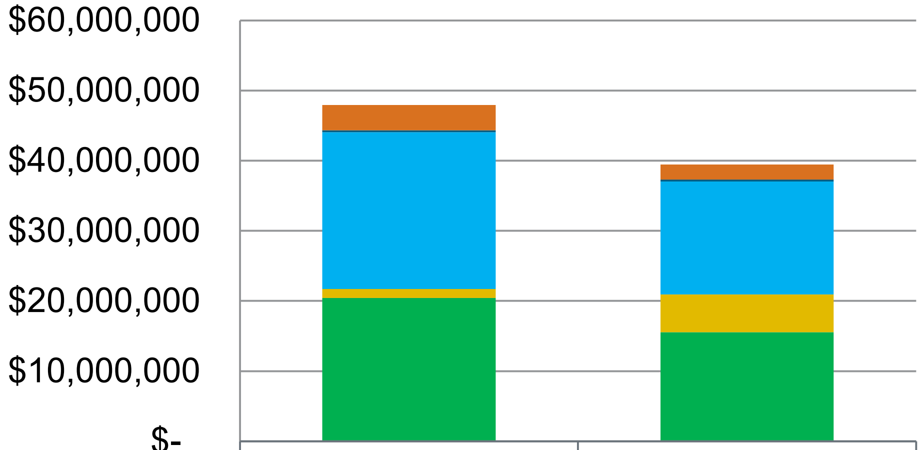
The Biochemical Technology Area will be reviewing 32 projects this week





Budget: Thermochemical R&D (numbers after rescission)

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



	FY12	FY13
Administrative	$3,586,766	$2,154,660
International	$267,418	$281,700
Competitively Selected Projects	$22,380,408	$16,079,109
Analysis	$1,260,000	$5,371,000
Lab Core R&D	$20,439,455	$15,563,279

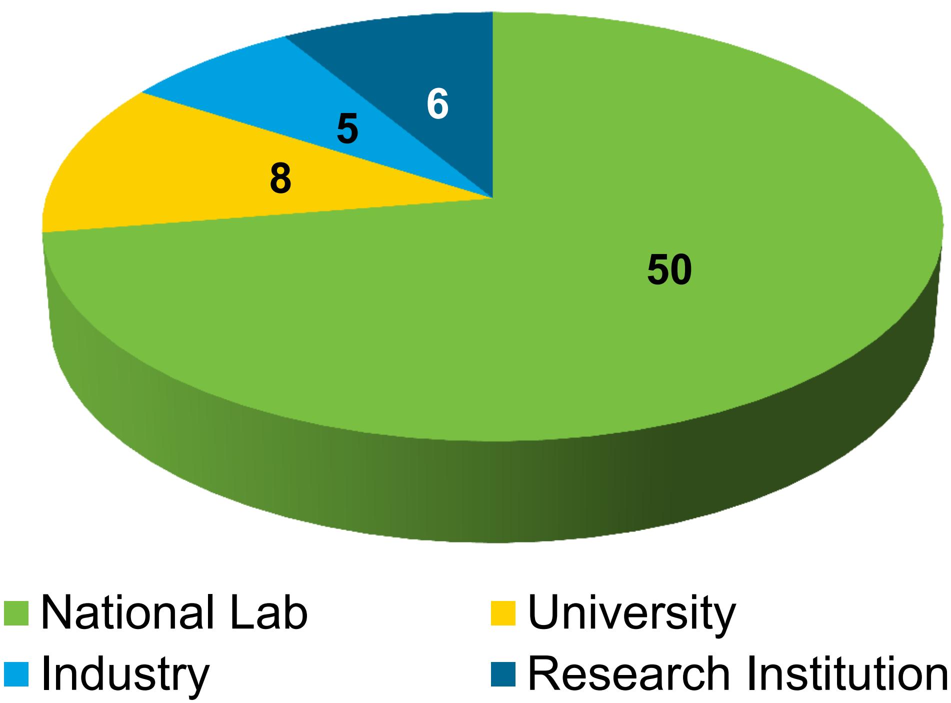
- Overall, TC funding decreased from ~$48m to $39.5m, as gasification R&D was de-emphasized.
- Analysis activities increased by $4m for updating and developing design cases and new work in computational modeling of pyrolysis and direct liquefaction or catalytic upgrading technologies.
- Lab Core R&D decreased from FY12-13, as FY12 funding was at its peaked for the gasification to ethanol integrated pilot validation tasks.
- ~ $16m in FY12 was directed at new projects from BOSC and USDA-DOE Joint Solicitation FOAs.
- ~ $12m in FY13 will be used to select new projects CHASE Bio-oil Pathways FOA.

Thermochemical Bio-Oil Conversion Project Portfolio

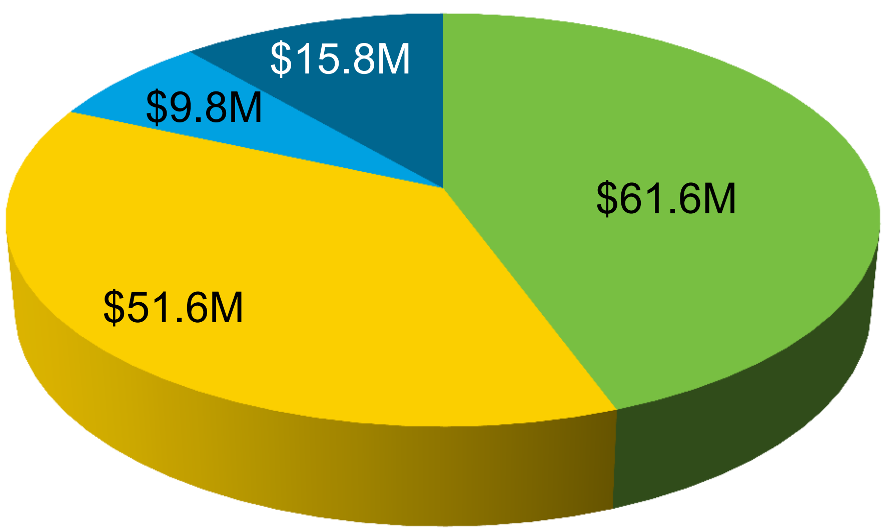
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

The Thermochemical Bio-Oil Technology Area will be reviewing 69 performers in 44 project presentations this week

Bio-Oils: Portfolio Performers Reviewed



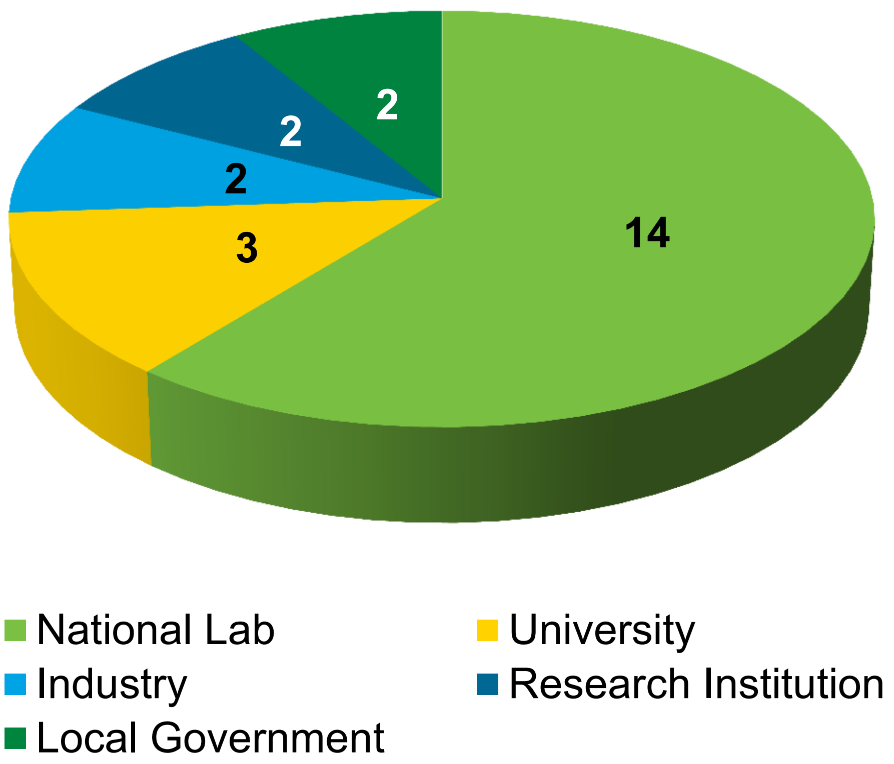
Bio-Oils: Total DOE Funding



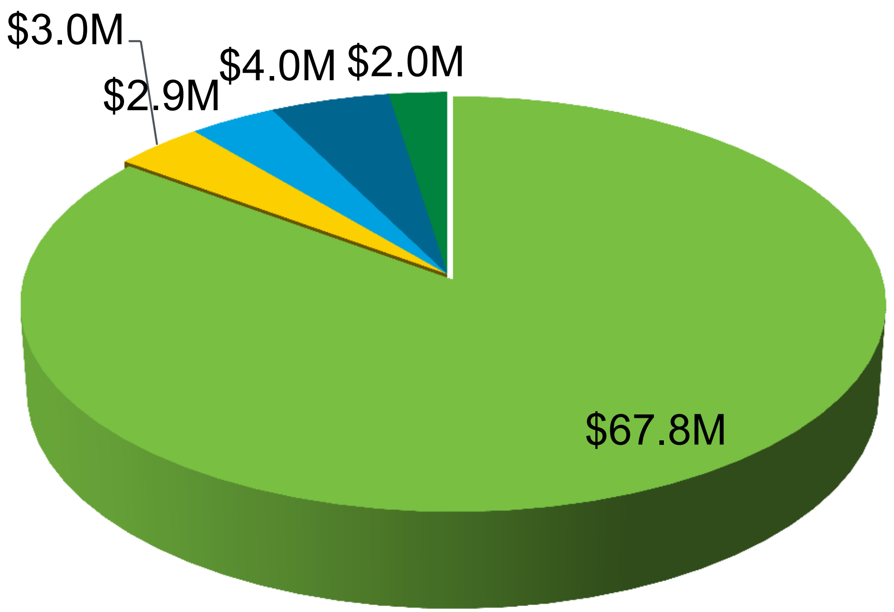
Thermochemical Gasification Conversion Project Portfolio

The Thermochemical Gasification Technology Area will be reviewing 23 projects this week

Gasification: Portfolio Performers Reviewed



Gasification: Total DOE Funding



Direct and Competitive Funding

Direct Lab Funding

- Substantial and unique capability
- Fundamental or specialized work benefitting many stake-holders
- Consistency of approach
- Third-party validation work
- The need to make R&D data publically available
- Nature of work requires FFRDC relationship
- Developing standard analytic procedures for dissemination and general use
- Work at early stage and unlikely to attract significant cost-share

Competitive (industry and lab and universities etc. eligible)

- Moving technology from fundamental to applied
- Transition of technology from applied research to development/application
- Areas where all entities have complementary capabilities/background

Competitive (industry only)

- Demonstration/commercialization projects
- IP essential to successful commercialization
- Significant resources required
- Significant cost-share required
- Market knowledge and/or commercialization experience essential for success.

BETO Conversion R&D Staff

Biochemical Staff

- Kevin Craig (Acting Program Manager)
- Bryna Berendzen
- Gene Petersen
- Joyce Yang
- Leslie Pezzullo
- Katy Christiansen (AAAS Fellow)

Thermochemical Staff

- Kevin Craig (Program Manager)
- Liz Moore
- Melissa Klembara
- Paul Grabowski (also on D&D staff)
- Prasad Gupte
- Nichole Litvinas (AAAS Fellow)

BETO Conversion R&D Staff

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Conversion Contractors

- Art Wiselogel (CNJV)
- Christine English (CNJV)
- Cynthia Tyler (CNJV)
- Gina Lynch (CNJV)
- Jessica Phillips (CNJV)
- Josh Messner (CNJV)
- Kara Stephens (CNJV)
- Ryan Livingston (BCS, Incorporated)
- Sarah Luchner (BCS, Incorporated)
- Trevor Smith (CNJV)

Conversion Agenda Overviews

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Biochemical

Monday-Thursday

Organized by process step

1. Major accomplishments
2. Platform analysis
3. Deconstruction processes
4. Conversion processes
5. Integrated processing and overall process improvement

Thermochemical Bio-Oils

Monday-Thursday

Organized by pathways & completive vs. core

1. Fast pyrolysis and catalytic upgrading
2. Ex-situ and in-situ catalytic fast pyrolysis
3. Hydropyrolysis
4. Hydrothermal and solvent liquefaction

Thermochemical Gasification

Monday and Tuesday

Organized by process step

1. Gasification
2. Syngas clean-up
3. Fuel synthesis

Joint Biochemical &Thermochemical

Wednesday 9:15am - 10:15am

National Advanced Biofuels Consortium (NABC)

Conversion Reviewers

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Biochemical

Carol Babb*	SAIC
Kevin Gray	Chemtex
Jim Kellis	DuPont Industrial Biosciences
Robert Kelly	NC State University
K. Thomas Klasson	USDA-ARS
Matthew Lipscomb	OPX Biotechnologies, Inc.

*** Lead Reviewer**

Thermochemical Bio-Oils

Don Stevens*	Cascade Science and Technology Research
Paul Bryan	Consultant, formerly with Chevron
Caroline Burgess Clifford	Penn State University
Dean Draemel	UC Berkeley. Formerly with ExxonMobile
Thomas Phillips	Intellection, LLC, Refinery Engineering Consultant

Thermochemical Gasification

Suresh Babu*	Brookhaven National Lab
Foster Agblevor	Utah State University
Jack Lewnard	Gas Technology Institute
John Scahill	Thermal Biofuels Consultants, LLC
David Sudolsky	Anellotech, Inc
Nathan Weiland	West Virginia University

GO FORTH AND DO

End of main slide deck

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Integrated Biorefinery Research Facility (IBRF)

- A unique $33.5 million pilot facility capable of supporting a variety of projects
- Can handle a wide range of biomass feedstocks and pretreatment processes
- Bioreactors from 10 L to 9000 L and separation and concentration equipment
- The IBRF can perform tests related to Biochemical Conversion:
  - Pretreatment
  - Enzymatic Hydrolysis
  - Fermentation
  - Product Separation and Recovery
  - Supporting Capabilities

With 27,000 ft^2 of high bay space, the IBRF provides industry partners with the opportunity to operate, test, and develop their own biorefining technology and equipment.

Advanced Biofuels Process Development Unit (ABPDU)

- A process development unit capable of small scale demonstrations of advanced biofuels production processes.
- **Location:** Emeryville, CA
- **Managing Laboratory:** LBNL
- **Outcome:** A managed small-scale user-facility for use by the Bioenergy Research Centers, National laboratories, Academia and Industry.
- **Scale:**
  - –Throughput: 100-200lbs/day (biomass
  - –Capacity: 3-5 gallons/per day (fuel) (at peak performance)

Unique Capabilities:

- Pretreatment: Solubilization by solvents
- Fuel flexible: Hydrocarbon chains, Esters and Alcohols
- Feedstock flexible

Unit Operations:

- Biomass Preprocessing
- Biomass Pretreatment
- Enzyme Production and Purification and Inoculation Tanks
- Biofuels Production
  - Alcohols such as ethanol and butanol
  - Advanced biofuels such as alkanes, cyclic alkanes and aromatics.
- Product Separations

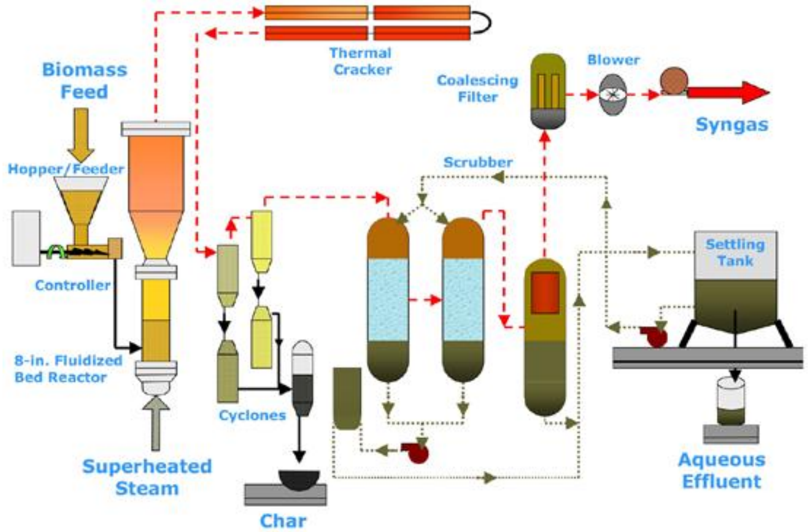
BERKELEY LAB

ABPDU Advanced Biofuels Process Demonstration Unit

NREL NATIONAL RENEWABLE ENERGY LABORATORY

Thermochemical Users Facility (TCUF)

- Consists of several complementary unit operations that can be configured to accommodate the testing and development of various reactors, filters, catalysts, and other unit operations.
  - Thermochemical Process Development Unit
    - 0.5 ton-per-day-feedstock [10-25 kg (22-55 lb) –per-hour]
    - Can be operated in either gasification or pyrolysis mode
    - Provides authentic biomass–derived product streams that are pre-cisely controlled, measured, and characterized
  - Catalytic Fuel Synthesis Reactors
  - Bench-Scale Biomass Conversion System
  - Fuel Synthesis Catalyst Test Facility



The analytical equipment in the TCUF can be taken on the road to provide online sampling at customer's sites:

- Molecular beam mass spectrometers
- Rapid cycle gas chromatographs
- Non-dispersive infrared sensors
- Thermal conductivity detectors
- Paramagnetic O_2 sensor
- Residual gas analyzers

Upcoming Potential Initiatives Biomass-Derived Carbon Fiber

- Produce carbon fiber (CF) from biomass
- Two Paths for R&D
  - ▶ Lignin
  - ▶ Bio-derived PAN precursor
- Enable lower cost precursors and lessen dependence on oil

EERE Partnerships

Innovations in Biomass Fractionation	Innovations in Renewable Chemical Manufacturing	Innovations in CF Manufacturing	Innovations in Automotive Lightweighting
BETO	BETO	AMO	VTO

Value Proposition

$0.10/lb cellulosic sugars & lignin that meets spec for biorefining → **10X** → **$1.00/lb** chemical intermediates that meets spec for CF → **5X** → **$5.00/lb** CF that meets specs for autos and trucks

Research Approach: Pathway Selection Process

March 2012
Working group convened, 18 potential pathways identified, 13 selected to move forward with initial analysis

July 2012
8 priority pathways selected from original 13

October 2012
Pathways prioritized and timeline for analysis developed

September 2013
Full design cases will be completed for 3 pathways (Biological Conversion of Lignocellulosic Sugars, AHTL, and Fast Pyrolysis (update))

Completed Activities → ***Planned Activities***

Preliminary TEA on proposed pathways performed by NREL and PNNL with input from other labs

September 2012
PNNL/NREL completed joint milestone report detailing analysis effort

April 2013
Technical memos published for 7 new pathways to hydrocarbon biofuels

September 2014
Full design cases will be completed for 5 additional pathways (*ex situ* and *in situ* Catalytic Pyrolysis, Algal Lipid Upgrading, and Catalytic Upgrading of Lignocellulosic Sugars, Syngas Upgrading)

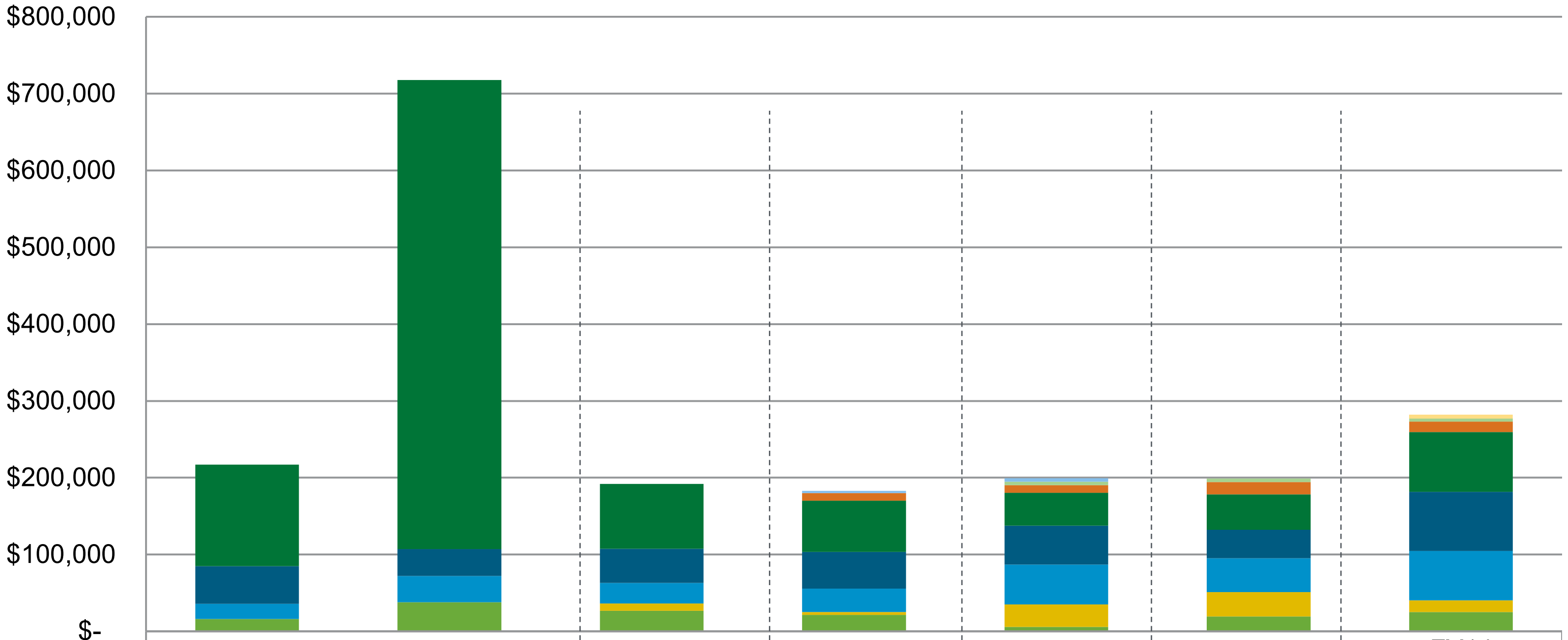
Criteria for selection included:

- Feasibility of achieving programmatic cost goal of $3/gal
- Near/Mid/Long-term techno-economic potential
- Potential national impact
- Feedstock availability/flexibility
- Data availability across the full pathway
- Co-product economics
- Potential volumetric impact in 2030
- Environmental Sustainability

Historical Budget Information

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

BETO Budget History



	FY09	FY09 ARRA	FY10	FY11	FY12	FY13	FY14 Request
SBIR/STTR				$2,716	$4,281		
NREL Lab Facilities							$5,000
Biopower/Cookstoves					$4,829	$4,487	$4,000
Analysis/Sustainability				$10,000	$9,813	$15,830	$13,500
Int Biorefineries	$132,000	$611,000	$84,278	$66,695	$42,897	$46,248	$78,000
Biochem	$49,000	$35,000	$44,440	$47,765	$50,733	$37,075	$77,000
Thermochem	$20,000	$34,000	$26,830	$30,184	$51,685	$43,982	$64,000
Algae Feedstock	$-	$-	$9,250	$3,895	$29,067	$31,659	$15,500
Feedstock Infrastrucure	$16,000	$38,000	$26,962	$21,440	$5,971	$19,523	$25,000

Accomplishments and Ongoing Work

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Innovative Biosynthetic Pathways – 2012 ($~10M)
- **Goal**: Utilize synthetic biology techniques to an applied research topic to improve techno-economic analysis for unit operation(s) in biomass processing routes for the production of hydrocarbon biofuels and biofuel precursors, as well as bioproducts and chemicals.
- **Awards**: Lygos, Inc, Pacific Northwest National Laboratory, Texas AgriLife, J. Craig Venter Institute, Novozymes

Biochemical Process Integration – 2011 ($36M)
- **Goal**: Show improvements to biochemical conversion unit operations for hydrocarbon fuel production in one unit operation, two or more unit operations or one or more unit operation using heterotrophic algae.
- **Awards**: Michigan Biotechnology Institute, Texas Engineering Experiment Station, Virent Energy Systems, Genomatica, General Atomics (terminated), Virdia (formerly HCL, Cleantech)

Enzyme Development for Saccharification – 2008 ($33.8M)
- **Goal**: Maximize glucose *and* xylose yields by developing robust enzymes requiring reduced protein loading levels
- **Awards**: Danisco, DSM, Novozymes and Verenium (now know as BP Biofuels)

Ethanologen Strain Development – 2007 ($23M)
- **Goal**: Increase microorganism productivity for ethanol production (titer, rate and yield)
- **Awards**: Cargill, DuPont, Mascoma, Purdue University and Verenium (now known as BP Biofuels)

Key Biochemical Technical Improvements

Significantly reduced enzyme loadings (from ~60 mg protein/g cellulose to 19 mg/g) and reduced costs >20x; Developed strains capable of converting C_5 and C_6 sugars at total conversion yields >95%.

Bottom Line

Collectively made sufficient progress on technical targets to meet the overall goal of $2.15 MESP.

These were validated by a fully integrated 1 ton/day validation run

Pyrolysis and Liquefaction Technologies Accomplishments and Current Efforts

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

CHASE Bio-Oils Pathways – 2013 ($12M, closes Feb 20, 2013)

- **Goal**: Use fundamental knowledge to inform R&D breakthroughs in carbon, hydrogen, and separation efficiencies in pyrolysis and liquefaction technologies to make gasoline, diesel, and jet fuels
- **Awards**: TBD

Bio-oil Stabilization and Commoditization – 2012 ($11.4M)

- **Goal**: Work with the petroleum refinery industry on R&D to make bio-oils an acceptable feedstock and defining those specification for use in refineries, thus leveraging capital and economies of scale.
- **Awards**: Stevens Institute of Technology, Southern Research Institute, Sapphire Energy, University of Georgia Research Foundation, Iowa State University, IN, PNNL, Gas Technology Institute

Thermochemical Intermediates Upgrading – 2011 ($12M)

- **Goal**: Demonstrate the ability to produce intermediate-hydrocarbon process, or the ability to produce transportation fuel from any intermediate.
- **Awards**: LanzaTech, Virent Energy Systems, Inc., Research Triangle Institute

Bio-Oil Upgrading – 2010 ($7M)

- **Goal**: Demonstrate ability to produce hydrocarbon transportation fuel that can be blended at up to 30 wt% or an upgraded bio-oil compatible with existing petroleum refining unit operations
- **Awards**: W.R. Grace & Company, PNNL, GTI, Battelle Memorial Institute

Pyrolysis Oil Stabilization – 2008 ($7M)

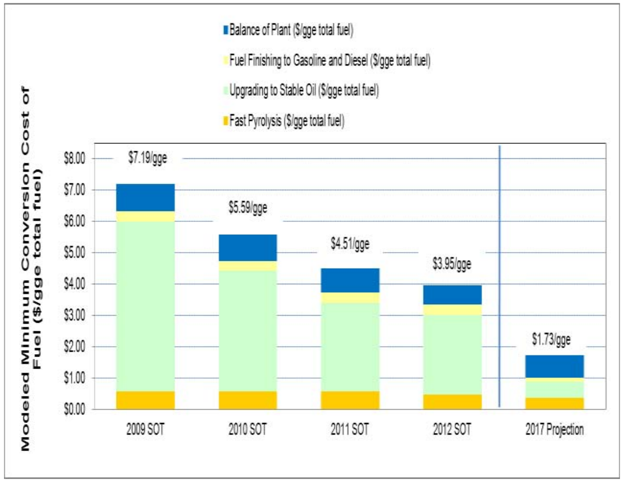
- **Goal**: Develop processes or techniques that stabilize fast pyrolysis bio oils generated from woody biomass
- **Awards**: Honeywell's UOP, Virginia Tech, Iowa State University, Research Triangle Institute, University of Massachusetts – Amherst

Bio-oils R&D Goal

By 2017, achieve a conversion cost of $1.73 per gallon of gasoline equivalent (gge) total fuel (or $1.83 /gal, $2011) via a bio-oil pathway.

Bottom Line

2012 State of Technology currently at $3.95/gge, with the biggest cost barrier in catalytic upgrading.



FY14 Budget and Future R&D: Biochemical Conversion

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

(Dollars in Thousands)	FY 2012 Current	FY 2013	FY 2014 Request
Biochemical Conversion	**50,733**	**37,075**	**77,000**
Carbon Fiber Initiative	—	—	20,000
Waste-to-Energy	—	—	5,000
Incubator Program	—	—	10,000

FY 2014 Activities

- Biochemical Conversion R&D includes both deconstruction of the biomass, as well as upgrading of the intermediates into renewable hydrocarbon fuels and chemicals.
- Activities will focus on optimizing biomass deconstruction technologies, reducing the cost of intermediates, and exploring innovative upgrading technologies for maximum carbon utilization.
- Funds are increased to initiate three new programs beyond fuels to include use of wastes to produce energy and products, lignin and cellulosic sugar utilization to produce carbon fibers, and a new incubator program.

FY14 Budget and Future R&D: Thermochemical Conversion

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

(Dollars in Thousands)	FY 2012	FY 2013	FY 2014 Request
Thermochemical Conversion	51,685	43,982	64,000
Incubator Program	—	—	10,000

FY 2014 Activities

- Continue competitive and core R&D projects to address technical barriers to converting biomass to bio-oil intermediates via pyrolysis or direct liquefaction followed by catalytic upgrading to produce finished fuels or petroleum refinery feedstock.
- Focus indirect liquefaction R&D efforts on gaseous intermediates and mixed oxygenate upgrading to produce gasoline, distillate, and jet range hydrocarbons from biomass in support of the programmatic goal of $3/gge by 2022.
- Develop techno-economic analysis and associated design cases that include cost projections and technical targets for direct and indirect liquefaction pathways to make gasoline, diesel, or jet fuels at $3/gge by 2022.
- Initiate new Incubator Program to enable small business innovations.

Research Approach: Pathways Included in Initial Analysis

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Technology Area	Pathway
Sugars	Fermentation of Sugars via Heterotrophic Algae to Hydrocarbons
	Fermentation of Sugars to Hydrocarbons
	Catalytic Upgrading of Sugars to Hydrocarbons
Oils	Catalytic Pyrolysis – ex situ
	Catalytic Pyrolysis – in situ
	Hydropyrolysis
	Hydrothermal Liquefaction
	Fast Pyrolysis and Upgrading
Algae	Whole Algae Hydrothermal Liquefaction (HTL)
	Algal Lipid Extraction Upgrading to Hydrocarbons (ALU)
Gaseous Intermediates	Syngas to Methanol to Triptyls
	Syngas Fermentation and Upgrading to Hydrocarbons
	Landfill Gas Upgrading to Hydrocarbons

Selection Criteria

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Criteria that were considered in the initial analysis included:

- Feasibility of reaching programmatic goal of $3/gal
- Near- (0-5 yr), mid- (5-10 yr), and long-term (10+ yrs) potential of technologies (both technical and economic potential, includes scalability)
- Potential for broad national impact (e.g., a platform intermediate that can go to multiple end products, even if design case does not depict all routes)
- Quantity of preferred feedstock available or ability to process multiple feedstocks
- Availability of data across the full pathway
- Availability and status of process models for part/all of conversion pathway
- Environmental sustainability (i.e. the pathway shows promise for reducing GHG emissions and does not present major concerns for water/air quality impacts or resource constraints, e.g., water, nutrients, etc.)
- Co-product economics
- Potential volumetric impact in 2030

Carbon Fiber Initiative Goals Roles & Responsibilities

BETO:
- Produce at least 2 metric tons of suitable clean lignin using advanced deconstruction/separation technologies
- From cellulosic sugars, produce at least 1 metric ton of suitable PAN precursor using advanced bioprocessing

AMO:
- Develop and demonstrate advanced technologies for converting conventional and alternative precursors to carbon fiber
- Advance high-volume composite design and manufacturing capabilities and transition technology to industry partners

VTO:
- Understand vehicle lightweighting requirements
- Develop integrated computational materials engineering ICME predictive tools and validation for structural lightweighting
- Enable low cost carbon fiber, composite design and manufacturing practices

- Carbon fiber for vehicles
  - $5/lb
  - Strength > 250KSI
  - Modulus > 25 MSI
  - Strain to failure > 1%
- Opens opportunities for other applications

Research Approach: Biochemical Pathways

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Pathway	Description	Cost Challenges
Biological conversion of sugars*	Production of sugars or biomass via enzymatic or non-enzymatic routes and subsequent biological processing to yield hydrocarbon fuel precursors (e.g. fatty acids, isoprenoids, etc.)	• Carbon efficiency and utilization by the microorganism (especially C5 sugars) • Organism production rates and inhibitor/toxicity issues • Separation & purification of product/intermediate streams
Chemical conversion of sugars*	Production of sugars or biomass carbohydrate derivates via enzymatic or non-enzymatic routes, and subsequent upgrading of the product stream through catalysis to yield a mix of hydrocarbons suitable for blending.	• Hydrolytic efficiencies • Chemical reforming • Fine-tuning polymerization/oligomerization • Separation & purification of product/intermediate streams
Catalytic upgrading of alcohols	*Production of sugars via enzymatic hydrolysis followed by fermentation to ethanol, and catalytic upgrading of ethanol to paraffins.*	• *Catalyst efficiency in alcohol upgrading* • *Enzyme efficiencies* • *Separation & purification of product/intermediate streams*

The CTAB workshop identified barriers that apply to these pathways

***Denotes that sugars actually refers to sugars or other lignocellulosic derivatives such as carbohydrate derivatives and lignin**

Research Approach: TC Bio-oil Pathways

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Pathway	Description	Cost Challenges
Conventional Fast Pyrolysis (FP) with Liquid Phase Upgrading	FP followed by a separate liquid phase upgrading step, then multi-stage hydrotreating	Lifetime and stability of upgrading catalysts Aqueous Phase Reforming
FP with Ex-Situ Vapor Phase Upgrading	FP followed by a separate vapor phase upgrading step, then one or two stages of hydrotreating	Trade-offs between Bio-oil Quality, Yields, and Severity of Hydrotreating Catalyst Lifetime and Stability
FP with In-Situ Vapor Phase Upgrading	FP in the same reactor as upgrading catalyst, followed by one or two stages of hydrotreating	Trade-offs between Bio-oil Quality, Yields, and Severity of Hydrotreating Catalyst Lifetime and Stability
Hydrothermal Liquefaction (HTL) or Solvent Liquefaction (SL)	Direct liquefaction in water (HTL) or solvent medium (SL), followed by catalytic upgrading. Used with high moisture feedstocks, such as algae	Algae Growth/Harvest High pressure vessels, higher liquid viscosity Algae Nutrient Recycle
Hydropyrolysis	FP in the presence of hydrogen and catalysts, followed by one stage of hydrotreating	High pressure reactor, Feed systems Catalyst Lifetime and Stability

The CTAB workshop identified barriers that apply to these pathways

Research Approach: TC Gaseous Intermediates Pathways

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Pathway	Description	Cost Challenges
Syngas Upgrading to Hydrocarbon Fuels Technology Pathway	Upgrading of biomass derived synthesis gas ('syngas') to hydrocarbon fuels. While this specific discussion focuses on the conversion of syngas via a methanol intermediate to hydrocarbon blendstocks, there are a number of alternative conversion routes for production of hydrocarbons through a wide array of intermediates from syngas.	• Develop catalysts that maximize carbon selectivity to desired hydrocarbon products • Maximize catalyst life and stability • Investigate alternative intermediates for hydrocarbon production • Consolidate and optimize process configuration • Demonstrate current design assumptions on larger scale systems

Key Barriers from MYPP/CTAB: Biochemical Pathways

Inherent to Biomass Utilization

- Biomass variability
- Biomass recalcitrance

Technical R&D Barriers to Processing Biomass

- Biomass fractionation
- Lower costs/improve quality of intermediates
- Pretreatment processing and costs
- Cellulase enzyme production, loading and costs
- Enable high performance separations technologies
- Improve catalyst performance – cleanup/conditioning & fuel synthesis
- Biochemical conversion process integration
- Biochemical/thermochemical interface
- Maximize carbon utilization
- Optimize reactor performance

Key Barriers from MYPP & CTAB: TC Bio-oil Pathways

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Bio-oils Technical Challenges and Barriers

- Feeding wet and dry biomass
- Catalyst and catalytic process comprehension
- Hydroprocessing and hydrogen considerations
- Separation systems and selective fractionation
- Sensors and controls
- Liquefaction of biomass and bio-oil stabilization
- Fuel synthesis and upgrading
- Bio-oil pathway process integration

Key Barriers from MYPP & CTAB: TC Gaseous Intermediates

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Gaseous Intermediates Technical Challenges and Barriers

- Feeding wet and dry biomass
- High-temperature gas production from biomass
- Low-temperature production of gaseous intermediates
- Gas cleanup and conditioning
- Validation of syngas quality
- Liquefaction of biomass and bio-oil stabilization
- Fuel synthesis and upgrading
- Sensors and controls
- Gaseous intermediates process integration

Key Accomplishments

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Successes in Saccharifcation and Fermentation

- On track to meet FY12 milestone to demonstrate enzyme loading of 3.6 mg protein/g carbohydrates while achieving a 90% conversion of xylan to xylose.
- In all validations, ethanol titer was improved by at least 15% and xylose utilization by at least 10% over benchmark

Bottom Line

On track to achieve 86% cellulose-to-ethanol and 85% xylose-to-ethanol at 20% total solids loading and meet or beat the required $0.04 fermentation cost reduction to hit the FY12 joule. **The latest (FY11) SOT beats the original projection ($1.80/gal in reality vs. $1.85/gal modeled cost)**

Successes In Gasification and Syngas Conversion

- Warm gas clean up (inorganics)
- Designed catalysts and processing techniques for tar reforming
- Designed catalysts for mixed alcohols and yield ethanol catalysis
- Developed molecular and kinetic models for gasification and pyrolysis (will be leveraged for CFD modeling)

Bottom Line

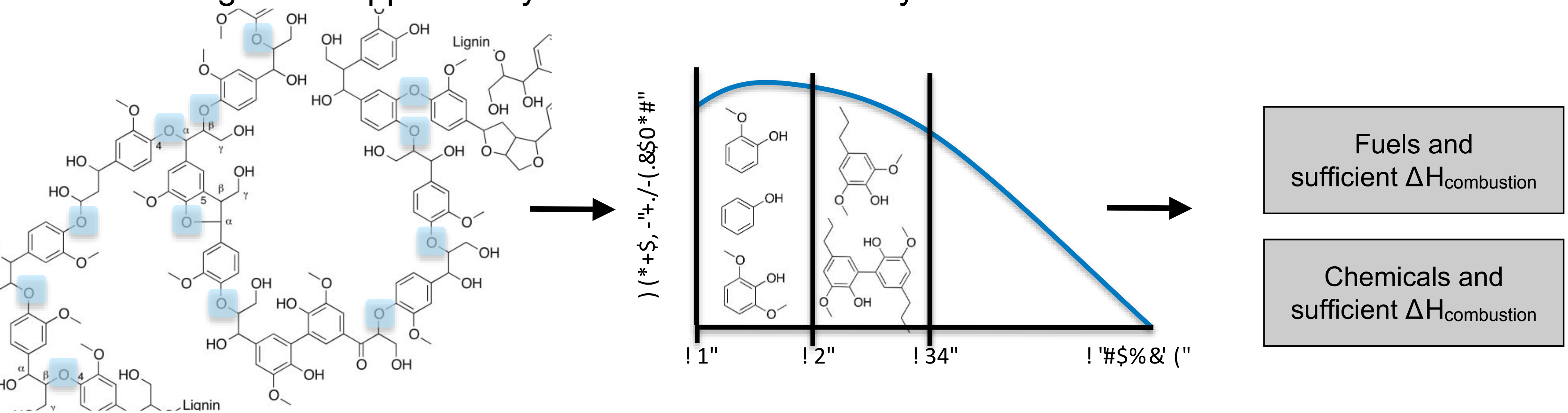
OBP is set to meet and demonstrate a conversion cost of **$1.31/gal EtOH (2007$) by the end of FY2012.** Cost reductions are largely attributed to advances in tar/methane reforming and fuels synthesis catalysis

FY 13 New Research Focuses

New Focus Areas:

- Bioproducts
- Lignin Utilization (example below)
- HC Catalyst Development

<u>Lignin Utilization:</u> Develop processes to produce fuels and value-added chemicals from lignin to meet cost targets in support of Hydrocarbon Fuel Pathways



- Successes to date:
  - Surveyed multiple lignin isolation options at bench-scale integrated with TEA model
  - Currently developing novel lignin upgrading pathways to produce both fuels and chemicals
- Will help address “Whole Barrel of Oil” initiative and development of integrated biorefinery
- Integrate work closely with TEA and LCA for economic and sustainability concerns