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Pathways to Hydrocarbon Biofuels:

Update on the Office's Techno-Economic Analysis Efforts

March 25, 2015

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Overview

- Progress on pathways to hydrocarbon fuels
- Purpose of Techno-Economic Analysis (TEA) and design cases
- TEA-Sustainability Coordination
- Request for Information (RFI): Input on Biofuel Pathways
- How BETO uses the design cases to inform R&D strategy

Representative Biofuel Pathways

Hydrocarbon Biofuel Pathways	Category
Whole Algae Hydrothermal Liquefaction	Wet Feedstock Conversion
Algal Lipid Extraction and Upgrading to Hydrocarbons	
Biological Conversion of Sugars to Hydrocarbons	Low Temperature Conversion
Catalytic Upgrading of Sugars to Hydrocarbons	
Ex-Situ Catalytic Pyrolysis	Direct Liquefaction
In-Situ Catalytic Pyrolysis	
Fast Pyrolysis and Upgrading	
Syngas to Mixed Alcohols to Hydrocarbons	Indirect Liquefaction

Criteria considered included:

- Data availability across the full pathway
- Feasibility of achieving cost goal of $3/gge
- **Broadly representative to encompass a range of technologies in the feedstock and conversion space**

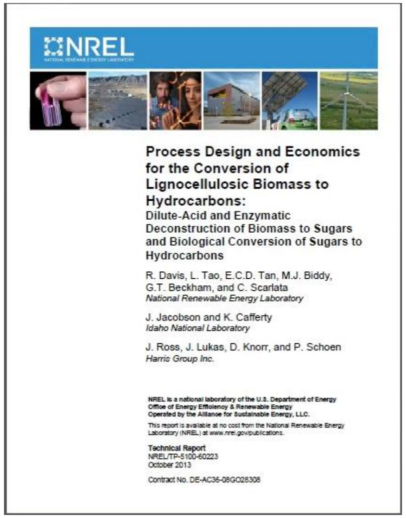
Techno-Economic Analysis (TEA) and Design Reports

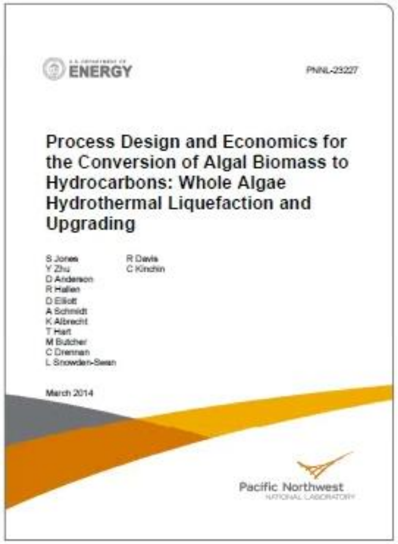
Purpose

- Setting R&D priorities
- Guiding program direction
- Identifying technology process routes and prioritize funding
- Benchmarking and tracking progress against goals

Design Case

- Target case that includes preliminary identification of data gaps and R&D needs
- Based on best available public information
- Includes an economic and environmental sustainability assessment
- Documented in a peer-reviewed Design Report
- Updated when sufficient advancements are made to the state of understanding of the process design





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Pathway TEA – Sustainability Coordination

- Goal: **Sustainable** and **economic** deployment of biofuel
- Combined TEA and environmental sustainability analysis helps to facilitate biorefinery designs that are economically feasible and minimally impactful to the environment
- Sustainability has historically been an underlying theme in TEA.
- Beginning in 2013, all new design cases and state-of-technology reports include a section on sustainability with metrics and sensitivity analysis

Design Report Environmental Sustainability Metrics	
GHG emissions	kg CO2e/GJ
Conversion Plant Fossil Energy Consumption	MJ/MJ
Biomass carbon to fuel efficiency	C in fuel/total input C
Water Consumption	m3/day, gal/gal
Fuel Yield	GGE/dry ton

Pathway Status Update

Category	Pathway	Design Report	Peer Review Presentation
Wet Feedstock Conversion	Whole Algae Hydrothermal Liquefaction (AHTL)	Published March, 2014	Algae, Tuesday 4:15-4:45 pm "Hydrothermal Liquefaction Model Development"
	Algal Lipid Extraction Upgrading to Hydrocarbons (ALU)	Published September, 2014	Algae, Tuesday 3:45-4:15 pm "Algal Biofuels Techno-Economic Analysis"
Low Temperature Conversion	Biological Conversion of Sugars to Hydrocarbons	Published in October, 2013	BC, Monday 3:15-3:45 pm "Biochemical Platform Analysis"
	Catalytic Upgrading of Sugars to Hydrocarbons	Published March, 2015	BC, Monday 3:15-3:45 pm "Biochemical Platform Analysis"
Direct Liquefaction	Fast Pyrolysis and Upgrading	Published November, 2013	TC, Monday 1:20-1:50 pm "Analysis and Sustainability Interface"
	Ex Situ Catalytic Pyrolysis	Published March, 2015	TC, Thursday 9:45-10:15 "Thermochemical Platform Analysis"
	In Situ Catalytic Pyrolysis		
Indirect Liquefaction	Syngas Upgrading to Hydrocarbons	Published March, 2015	TC, Thursday 9:45-10:15 "Thermochemical Platform Analysis"

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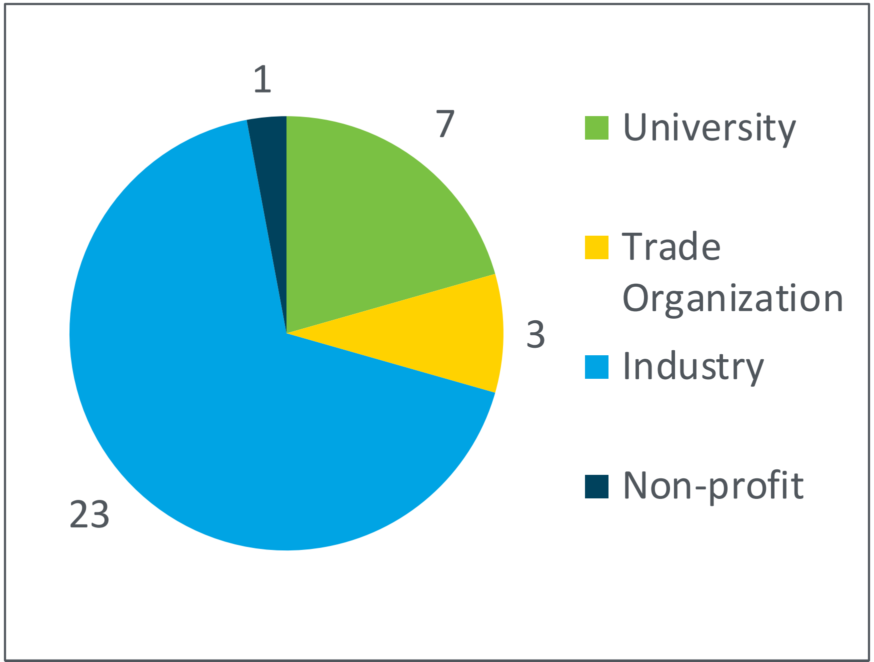
Request for Information: Input on Biofuel Pathways

- In May 2014, BETO issued a Request for Information (RFI) seeking stakeholder input on:
  1) the Office's eight representative biofuel pathways, and
  2) any other pre-commercial pathways the Office should consider.



The RFI received 34 total responses from industry, academia, and non-profit and trade organizations.

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Category I: Input on Representative Pathways

- Respondents were asked for input on BETO’s eight representative pathways, including:
  1. Pathway details;
  2. Critical barriers to; and
  3. Criteria that should be considered in evaluating new pathways.
- Respondents provided information on the performance of their pathways, providing an insight into industry performance of the representative pathways.
- Some respondents chose to provide proprietary information.

Pathway Characteristics
Product yields
State of technology
Process economics
Near-/mid-/long-term techno-economic potential
Time horizon for commercial relevance
Feedstock availability/flexibility
Potential volumetric impact in 2030
Environmental performance
Co-product economics

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Category I: Responses by Pathway

Category	Pathway	Number of Responses
Direct Liquefaction	Fast Pyrolysis and Upgrading	0
	Ex-Situ Catalytic Pyrolysis	1
	In-Situ Catalytic Pyrolysis	1
Low Temperature Conversion	Biological Conversion of Sugars to Hydrocarbons	4
	Catalytic Upgrading of Sugars to Hydrocarbons	2
Wet Feedstock Conversion	Whole Algae Hydrothermal Liquefaction (AHTL)	6
	Algal Lipid Extraction Upgrading to Hydrocarbons (ALU)	5
Direct Liquefaction	Syngas Upgrading to Hydrocarbons	6

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Category II: Input on Additional Pathways

- Respondents were asked for information about additional pathways not included in BETO's suite of eight representative pathways, including:
  1. Pathway details;
  2. Critical barriers; and
  3. Criteria that should be considered in evaluating new pathways.
- Information provided on 18 additional pathways
- Responses also included general comments on BETO's strategy and approach.

Pathway Characteristics
Product yields
State of technology
Process economics
Near-/mid-/long-term techno-economic potential
Time horizon for commercial relevance
Feedstock availability/flexibility
Potential volumetric impact in 2030
Environmental performance
Co-product economics

Category II: Additional Pathways

Enzymatic Conversion of Sugars to High-Yield Hydrogen	**Solvent enhanced hydrothermal liquefaction**
Hydrolysis and Catalytic Decarboxylation	Heterotrophic fermentation
Upgrading biogas to hydrocarbon fuels	Algae-based Photosynthetic Conversion of CO_2
CO-rich industrial gas residues to chemical intermediates, CO_2 gas fermentation to hydrocarbon intermediates (lipids)	Other Algae-derived non-drop in fuels
Bio-Oil Gasification	**Other Algae-derived non-fuel products**
Pyrolysis with Liquid-Phase Post Processing of Bio-Oils	Energy Efficient Extraction of Bio-oils from Algal Biomass
Thermochemical Conversion of Ethanol to Butanol	Hydrocarbon Biofuels from Olefins
Multi-Modal Clean Thermal Biomass Conversion – biomass heated in a pressurized reactor yielding a biomethane gas and biochar	Conversion of Biomass to High Energy Density Oxygenated Fuel Blendstocks
Hydrothermal Liquefaction of Biosolids from Wastewater Treatment	Sewage Sludge-to-Power

RFI: Additional Comments and Next Steps

RFI responses also touched on:

- Non-hydrocarbon biofuels
- Bioproducts/co-products
- BETO’s pathway approach

Next Steps:

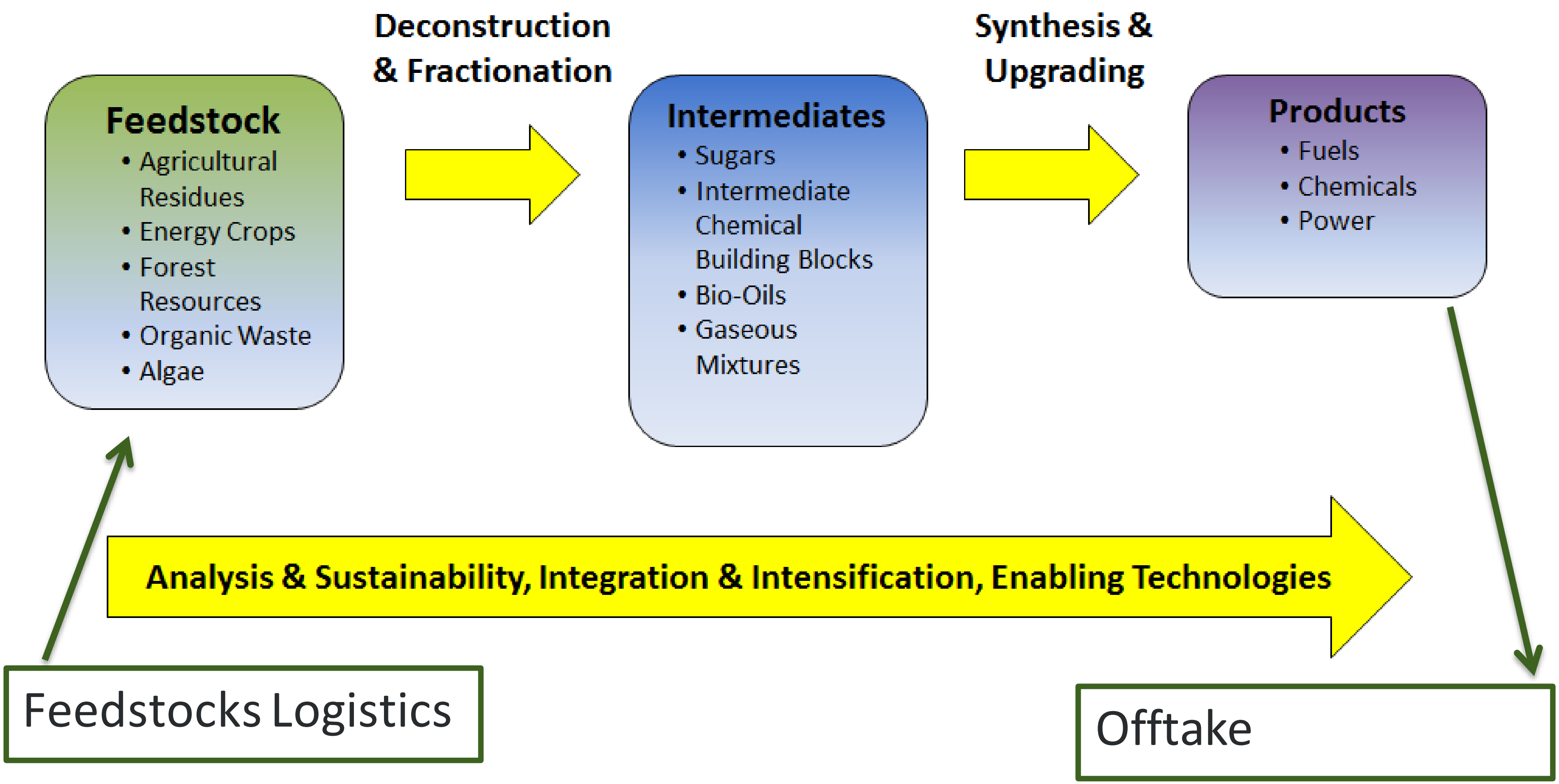
- Plan to issue similar RFI on a recurring basis

Pathways, Design Cases and Conversion

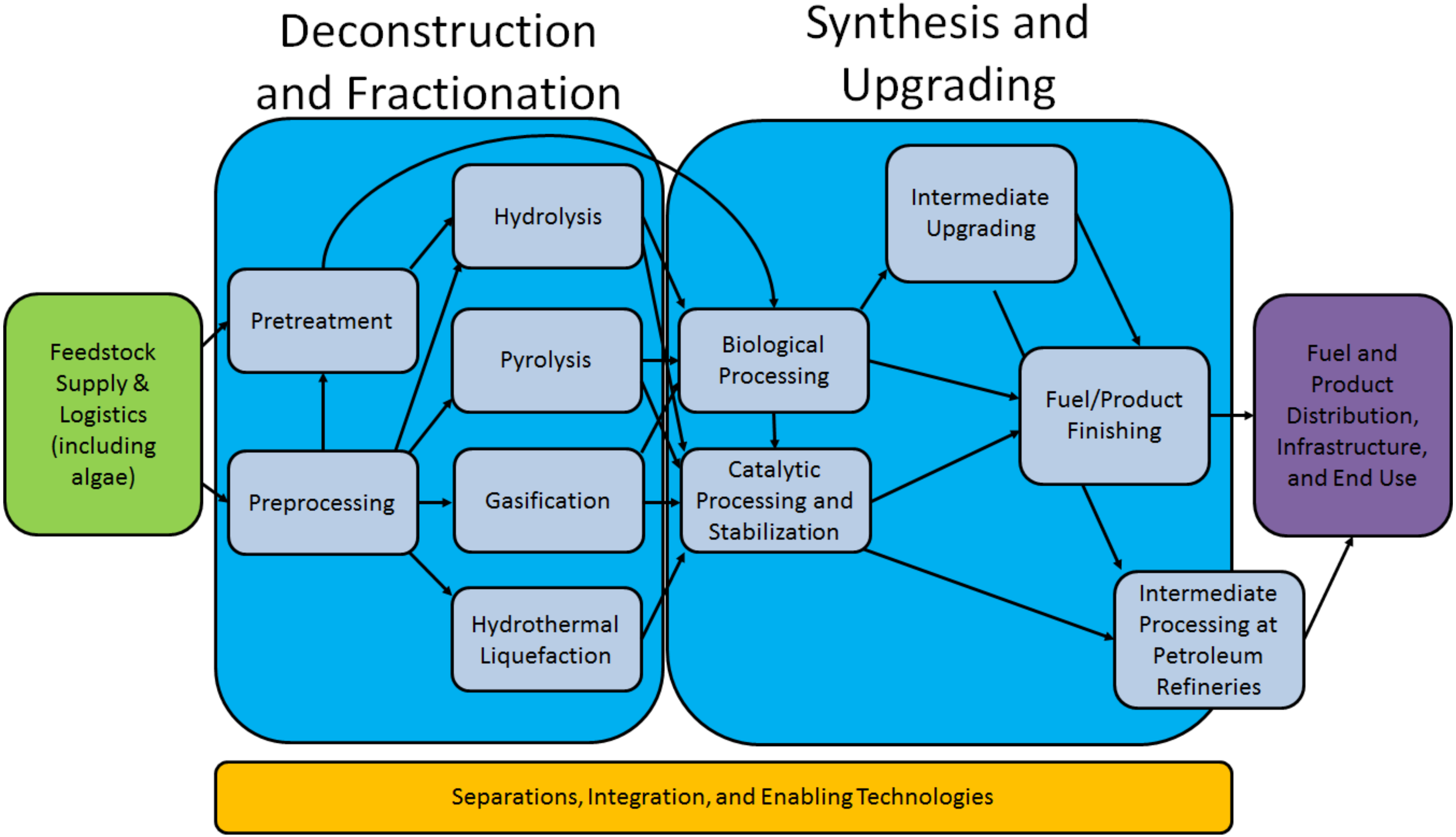
Two take away questions:

- What is BETO's R&D approach and how do design cases and pathways map on to that approach?
- How do the results from design cases help to inform Conversion R&D?

What does a conversion pathway look like?



Pathways are collections of technologies and interfaces



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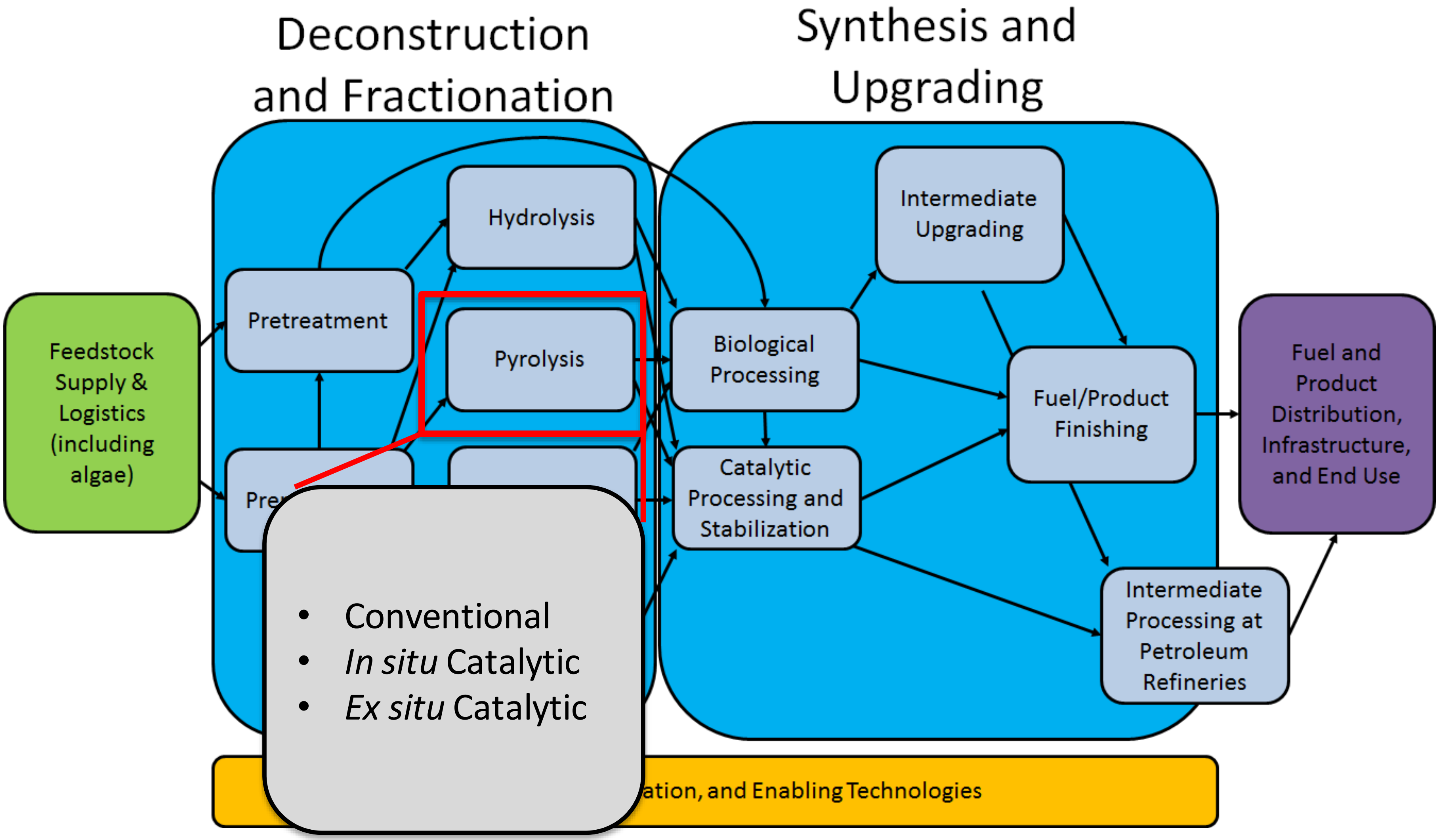
Within each technology area multiple variations exist



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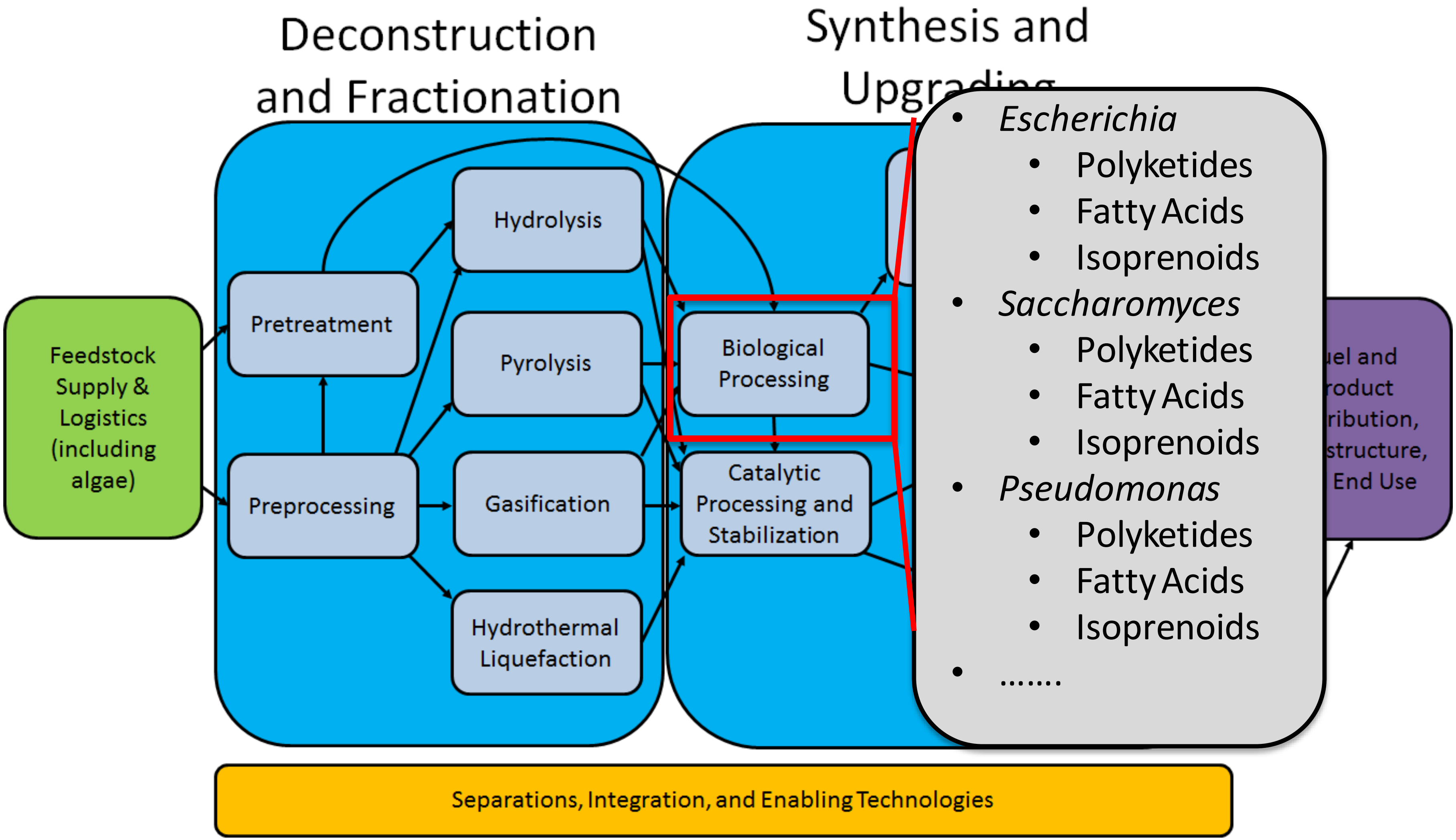
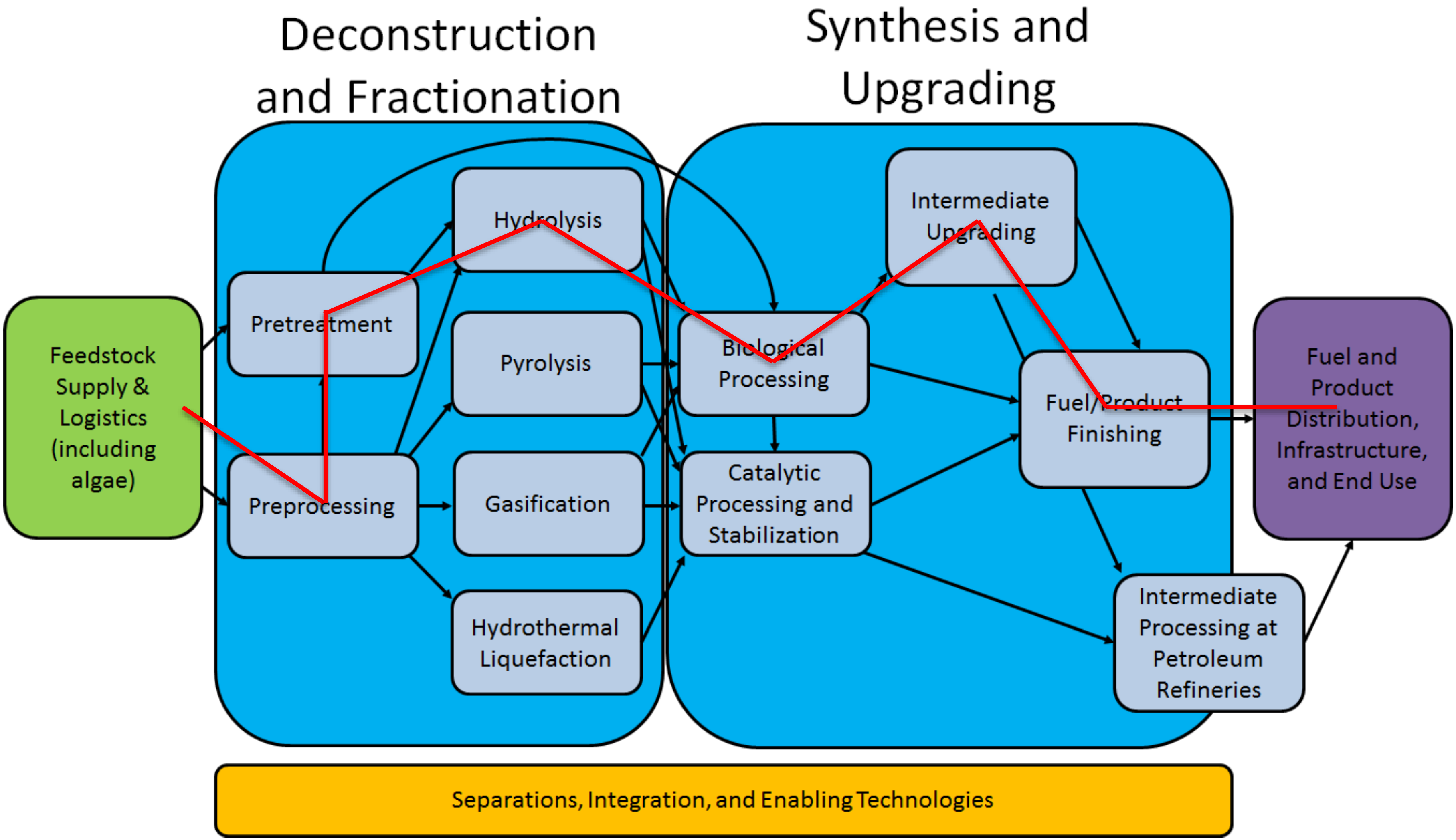
And can be quite granular...



What does a pathway look like in this context?



The goal of this R&D approach

- Diversify R&D in recognition that ultimately industry will decide which pathways are the most viable
- Enable progress in one technology to have effects across multiple different pathways
  - A new preprocessing technology might enable cost reductions in all pathways
  - A new hydrolysis technology would enable multiple low-temperature deconstruction pathways
- Recognize that different pathways involve technologies at various levels of development (components with different TRLs)

Design cases evaluate TEA for full pathways and enable LCA

Biological Renewable Diesel Blendstock (RDB) Process Engineering Analysis

Dilute Acid Pretreatment, Enzymatic Hydrolysis, Hydrocarbon (FFA) Bioconversion, Hydrotreating to Paraffins (RDB)

All Values in 2011$

Minimum Fuel Selling Price (MFSP):	**$5.35 /gal**
MFSP (Gasoline-Equivalent Basis):	**$5.10 /GGE**
Contributions: Feedstock	$1.85 /gal ($1.76/GGE)
Enzymes	$0.39 /gal ($0.37/GGE)
Non-Enzyme Conversion	$3.11 /gal ($2.96/GGE)
RDB Production	31.3 MMgal/yr (at 68 °F) (32.9 MM GGE/yr)
RDB Yield	43.3 gal / dry U.S. ton feedstock (45.4 GGE/ton)
Bioconversion Metabolic Yield	0.284 kg FFA/kg total sugars (79% of theoretical)
Feedstock + Handling Cost	$80.00 /dry U.S. ton feedstock
Internal Rate of Return (After-Tax)	10%
Equity Percent of Total Investment	40%

Capital Costs	
Pretreatment	$51,400,000
Neutralization/Conditioning	$2,200,000
Enzymatic Hydrolysis/Conditioning/Bioconversion	$75,400,000
On-site Enzyme Production	$12,400,000
Product Recovery + Upgrading	$26,600,000
Wastewater Treatment	$60,100,000
Storage	$3,400,000
Boiler/Turbogenerator	$76,000,000
Utilities	$8,800,000
Total Installed Equipment Cost	$316,300,000

Manufacturing
Feedstock + Handlin
Sulfuric Acid
Ammonia (pretreatme
Caustic
Glucose (enzyme pro
Hydrogen
Other Raw Materials
Waste Disposal
Net Electricity
Fixed Costs

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

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

J. Jacobson and K. Cafferty
Idaho National Laboratory

J. Ross, J. Lukas, D. Knorr, and P. Schoen
Harris Group Inc.

Design cases evaluate TEA & enable LCA for **full** pathways

Biological Renewable Diesel Blendstock (RDB) Process Engineering Analysis

Dilute Acid Pretreatment, Enzymatic Hydrolysis, Hydrocarbon (FFA) Bioconversion, Hydrotreating to Paraffins (RDB)

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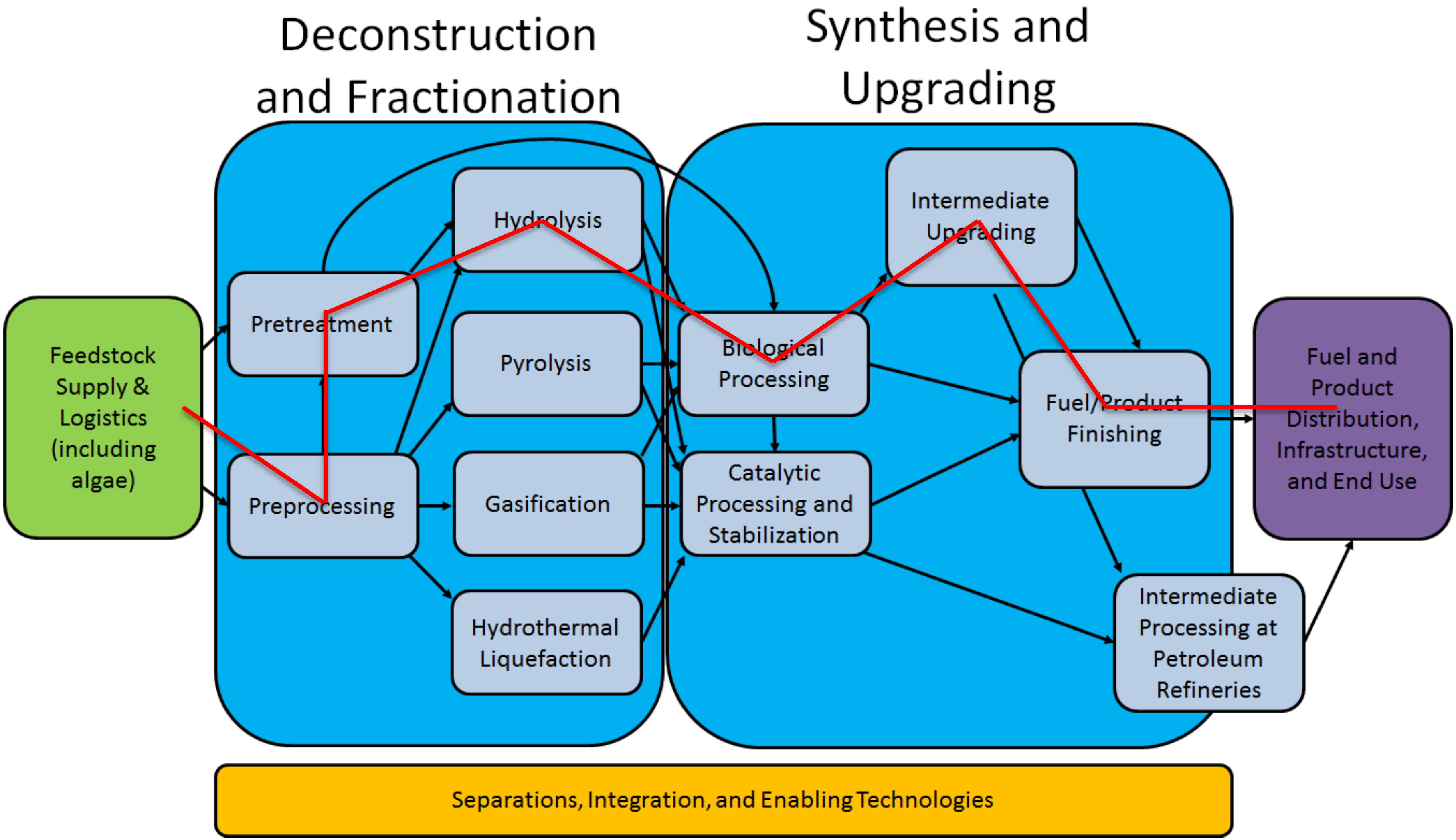
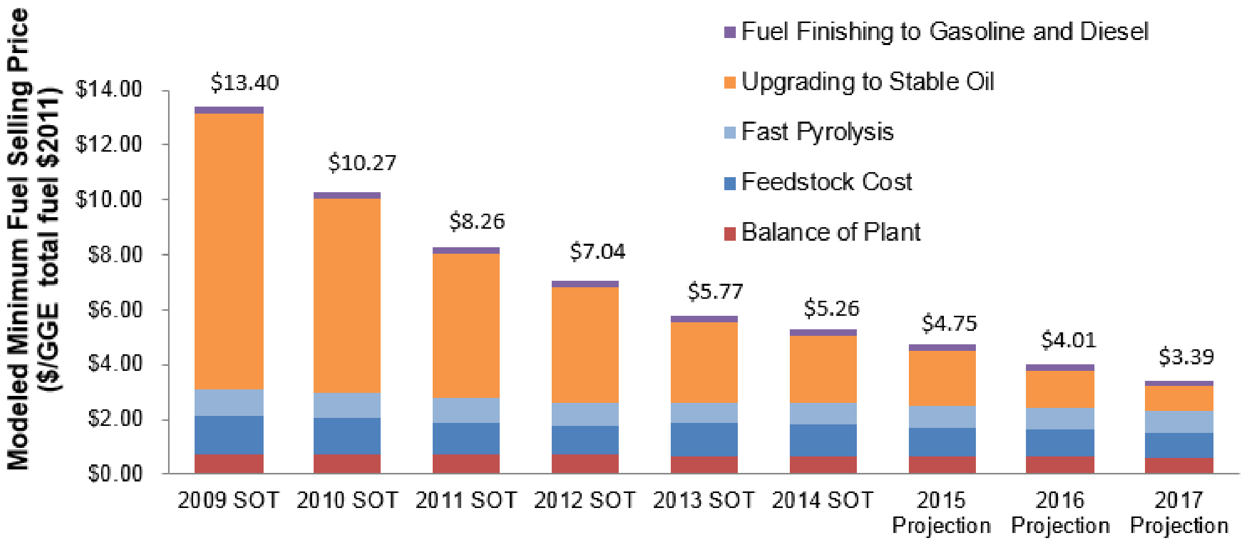
Dilute Acid Pretreatment, Enzymatic Hydrolysis, Hydrocarbon (FFA) Bioconversion, Hydrotreating to Paraffins

Mapping a representative pathway within conversion



Using a single design case to inform R&D

Take the Fast Pyrolysis and Upgrading case



- Allows us to focus R&D on the areas which contribute most to production cost
- Allows us to show progress from year to year in a relevant metric (MFSP)

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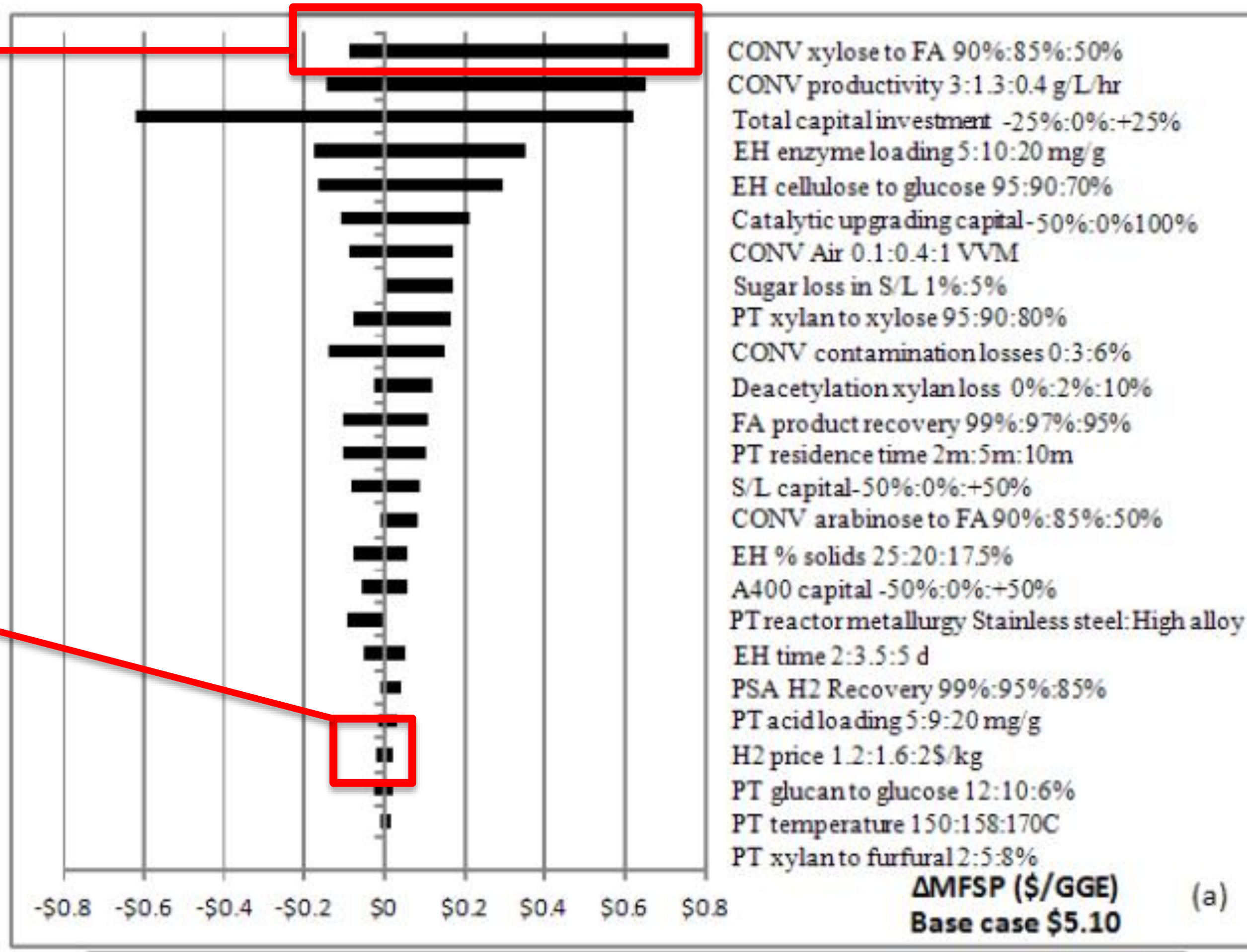
Using a single design case to inform R&D - Sensitivity

Take the Biological Upgrading case:

CONV xylose to FA 90%, 85%, 50%

H_2 price 1.2, 1.6, 2

- Not only highest cost areas, but most sensitive components



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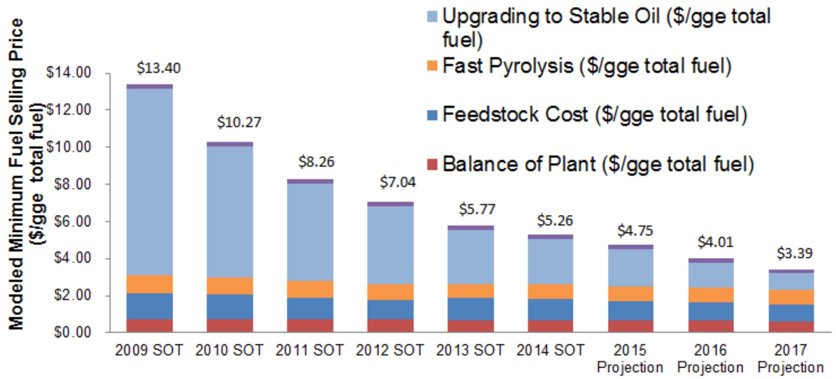
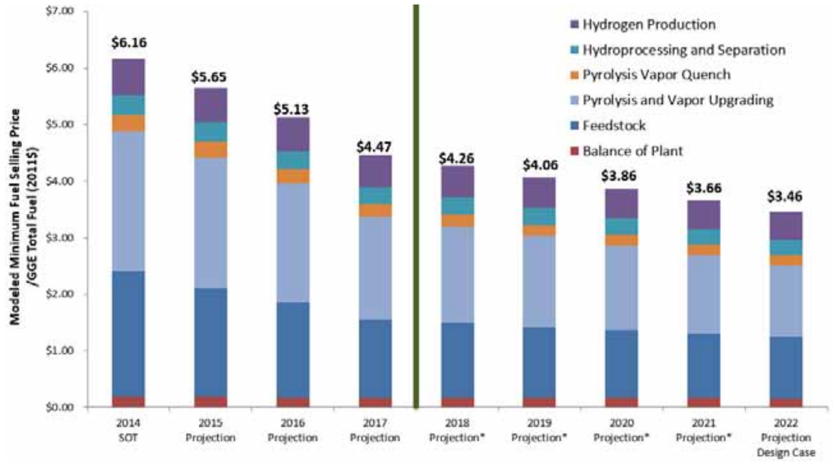
Related design cases can show overlapping R&D needs

Current Design Cases	R&D need
Ex Situ Catalytic Pyrolysis	High-temperature deconstruction to a bio-oil intermediate
In Situ Catalytic Pyrolysis	High-temperature deconstruction to a bio-oil intermediate
Fast Pyrolysis and Upgrading	High-temperature deconstruction to a bio-oil intermediate
Syngas to Mixed Alcohols to Hydrocarbons	High-temperature deconstruction to gaseous intermediates
Biological Conversion of Sugars to Hydrocarbons	Low-temperature deconstruction to sugar/organic intermediates
Catalytic Upgrading of Sugars to Hydrocarbons	Low-temperature deconstruction to sugar/organic intermediates
Whole Algae Hydrothermal Liquefaction	Upgrading of wet feedstocks
Algal Lipid Extraction and Upgrading to Hydrocarbons	Upgrading of wet feedstocks

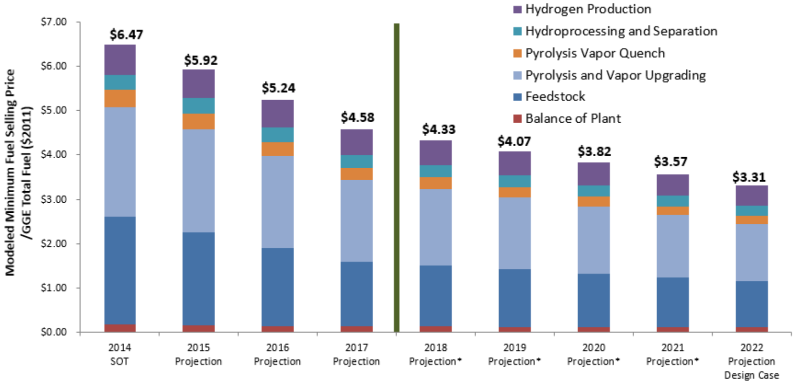
Using multiple design cases to inform R&D



Fast Py.



In situ



Ex situ

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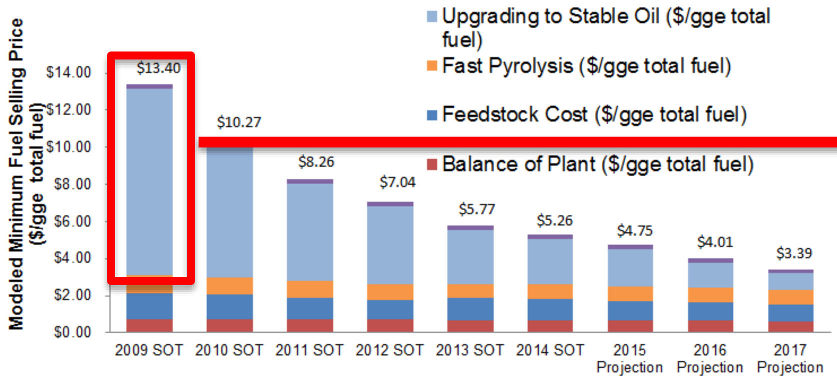
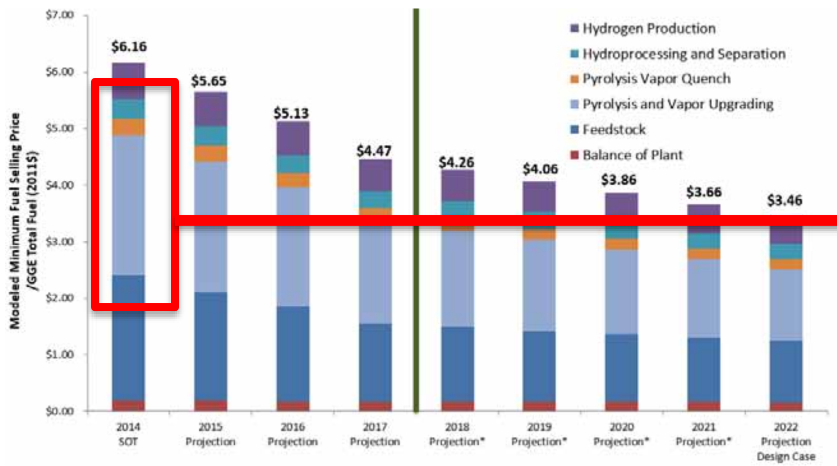
Using multiple design cases to inform R&D

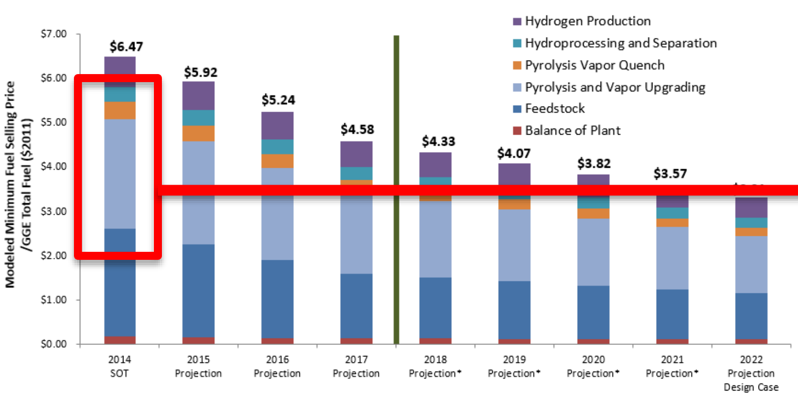


Fast Py.



In situ

Three related pyrolysis cases all show room for improvement in vapor upgrading costs



Ex situ

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Takeaway messages contribute to FOA development

CHASE (Carbon Hydrogen and Separations Efficiency)

- Efficiencies in High-Temperature Processes

BCU (Biochemical Upgrading)

- Deconstruction costs down due to cellulosic ethanol progress
- Bring down upgrading costs to hydrocarbon fuels/biochemicals

Pathways, Design Cases and Conversion Conclusions

How do the results from design cases help to inform Conversion R&D?

- Allows us to focus R&D on the areas which contribute most to production cost
- Allows us to show progress from year to year in a relevant metric (MFSP)

Summary and Next Steps

- TEA is critical for guiding program direction, setting R&D priorities, and tracking progress towards goals
- In 2013, eight representative technology pathways to hydrocarbon fuels were identified
- Effort leveraged ongoing work at DOE National Labs and NABC
- Design reports have been published for 6 hydrocarbon biofuel pathways
- Representative pathways allow a technology focus guided by TEA

Next Steps

- Continue to explore new pathway options (ongoing)

More information can be found on the BETO website:
http://www1.eere.energy.gov/biomass/technology_pathways.html

Backup

Relevant Presentations This Week (1/2)

Platform	Day	Time	Title	Organization	PI
Terrestrial Feedstocks	Monday	10:00	Feedstock Supply Chain Analysis	INL	Jacobson
Algal Feedstocks	Tuesday	3:45	Algal Biofuels Techno-Economic Analysis	NREL	Davis
	Tuesday	4:15	Hydrothermal Liquefaction Model Development	PNNL	Jones
Biochemical Conversion	Monday	1:10	Biochemical Conversion Feedstock Supply Interface	NREL	Nagle
	Monday	3:15	Biochemical Platform Analysis	NREL	Davis
	Tuesday	11:15	Waste-to-Energy Life-Cycle Analysis, Waste-to-Energy Techno-Economic Analysis	ANL	Han
	Tuesday	3:45	Catalytic Upgrading of Sugars	NREL	Johnson
	Wednesday	1:00	Biological Upgrading of Sugars	NREL	Beckham

Relevant Presentations This Week (2/2)

Platform	Day	Time	Title	Organization	PI
Thermo-chemical Conversion	Monday	1:20	Analysis and Sustainability Interface	PNNL	Jones
	Monday	4:15	Thermochemical Feedstock Interface	NREL	Carpenter
	Tuesday	10:15	Biological Pyrolysis Oil Upgrading	NREL	Beckham
	Tuesday	2:00	Catalytic Upgrading of Pyrolysis Products	NREL	Shaidle
	Thursday	9:45	Thermochemical Platform Analysis	NREL	Dutta
Analysis & Sustain-ability	Tuesday	1:00	Strategic Analysis and Modeling	NREL	Biddy
	Tuesday	1:45	High-Level Techno-Economic Analysis of Innovative Technology Concepts	PNNL	Jones
	Tuesday	3:20	Integration of Sustainability Metrics into Design Cases and State of Technology Assessments	NREL/PNNL	Biddy/ Snowden-Swan
	Tuesday	3:40	GREET Development and Biofuel Pathway Research and Analysis	ANL	Wang

Pathways Development Timeline

March 2012
Working group convened, suite of potential pathways identified, subset selected to move forward with initial analysis

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

July 2012
8 representative pathways selected from original suite

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

April 2013
Technical memos published for 7 pathways to hydrocarbon biofuels

October 2013
Design report completed for Biological Conversion of Sugars to Hydrocarbons pathway

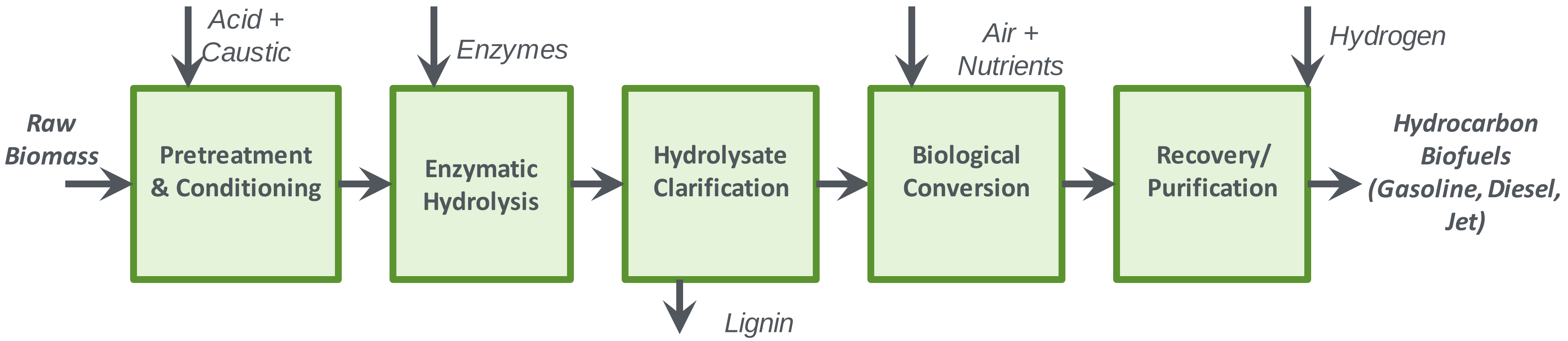
November 2013
Updated design report completed for Fast Pyrolysis and Hydrotreating Bio-oil Pathway

March 2014
Design report completed for Whole Algae Hydrothermal Liquefaction and Upgrading pathway

September 2014
Design report completed for Algal Lipid Extraction and Upgrading to Hydrocarbons pathway

March 2015
Full design cases completed for *ex situ* and *in situ* Catalytic Pyrolysis, Catalytic Upgrading of Sugars to Hydrocarbons and Syngas Upgrading

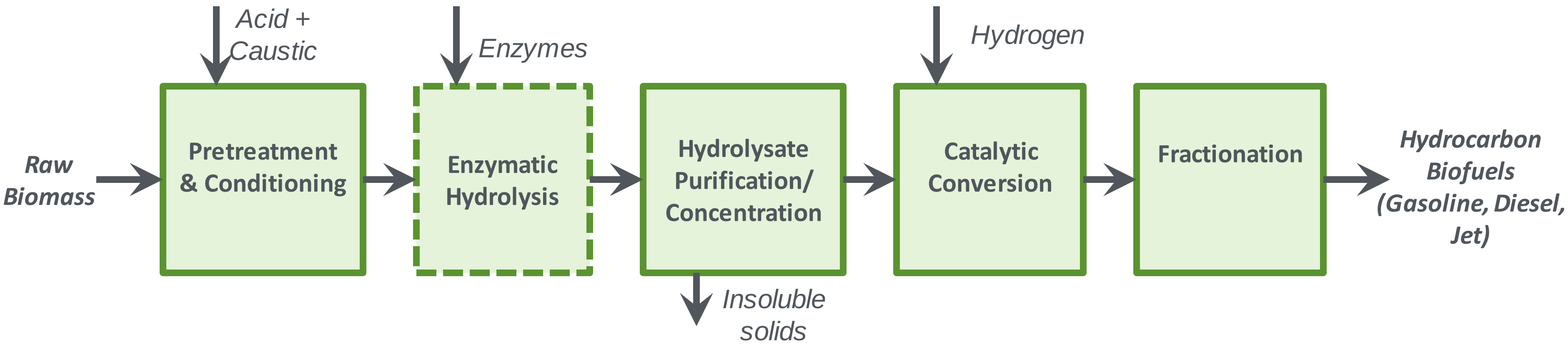
Biological Conversion of Sugars to Hydrocarbons



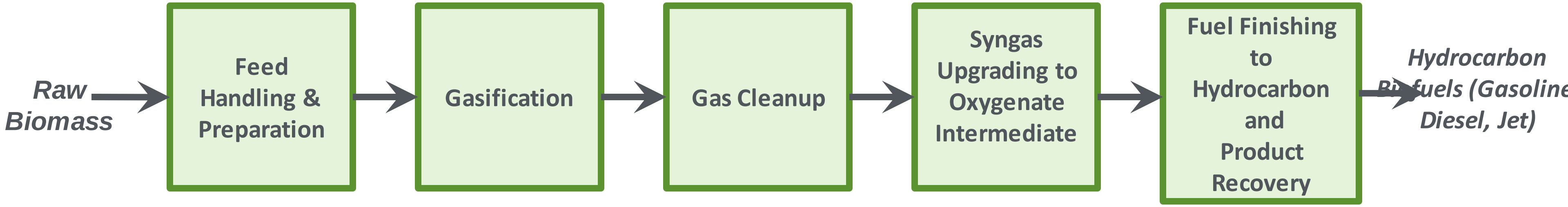
Status

- Design Case published in FY13
- http://www.nrel.gov/docs/fy14osti/60223.pdf

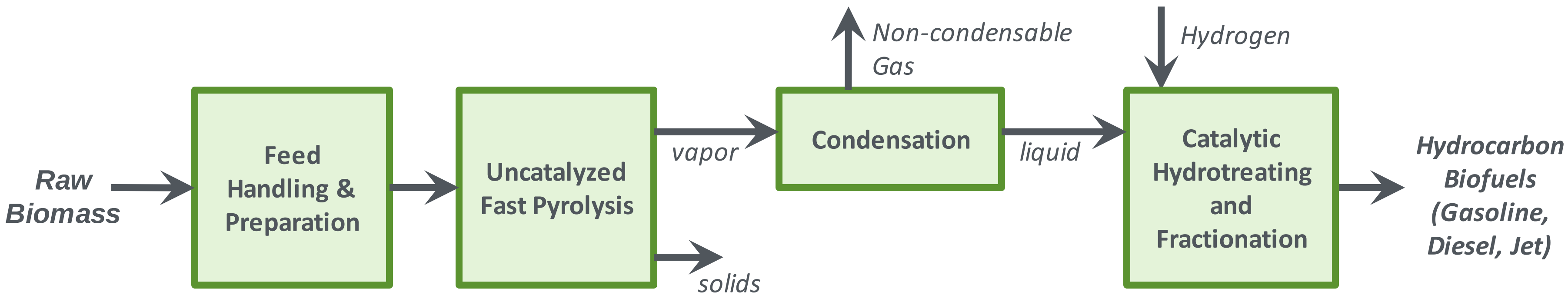
Catalytic Upgrading of Sugars to Hydrocarbons



Syngas Upgrading to Hydrocarbon Fuels

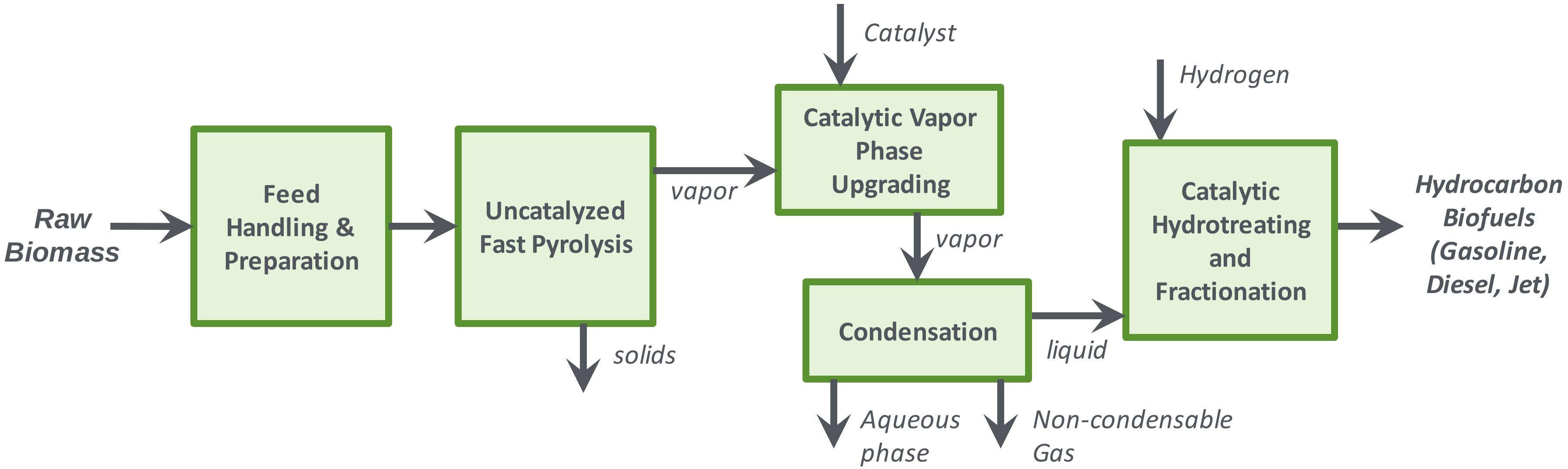


Fast Pyrolysis and Upgrading and Hydroprocessing



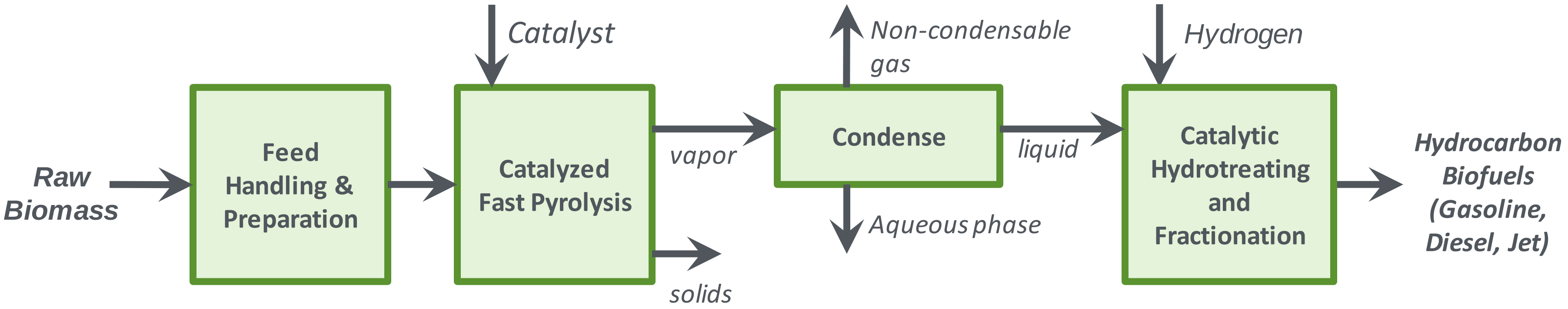
Biomass is rapidly heated in a fluidized bed reactor to yield vapors, which are condensed into a liquid bio-oil. This bio-oil is subsequently hydroprocessed to produce hydrocarbon biofuel blendstocks.

Ex situ Catalytic Fast Pyrolysis



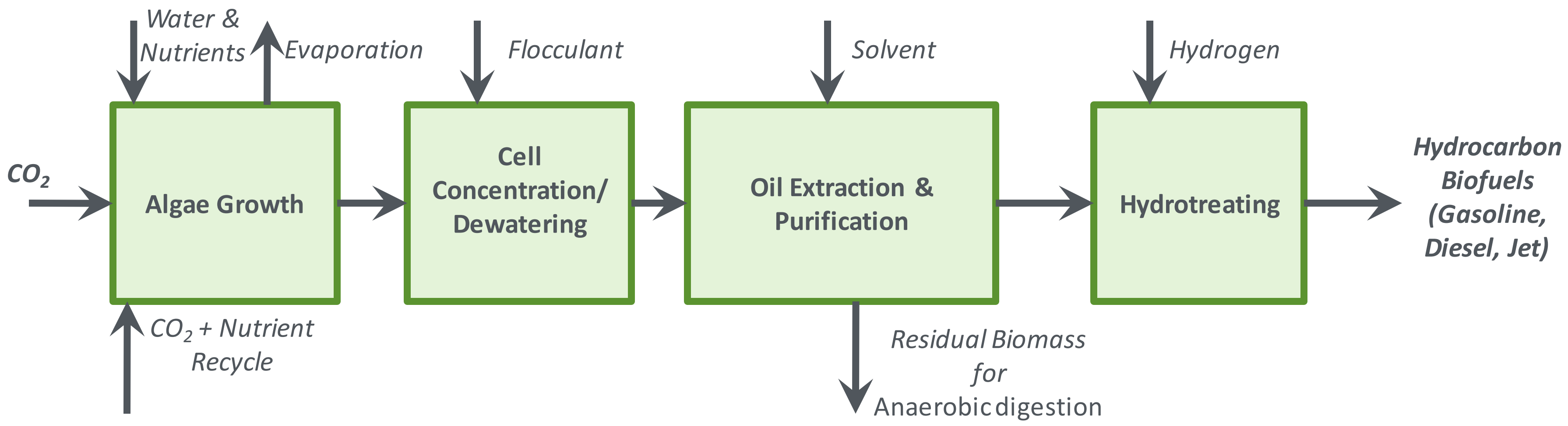
Biomass is rapidly heated in a fluidized bed reactor containing a catalyst to yield vapors, which are catalytically modified and condensed into a partially stabilized and deoxygenated liquid bio-oil. This stable bio-oil is subsequently upgraded to produce hydrocarbon biofuel blendstocks.

In situ Catalytic Fast Pyrolysis



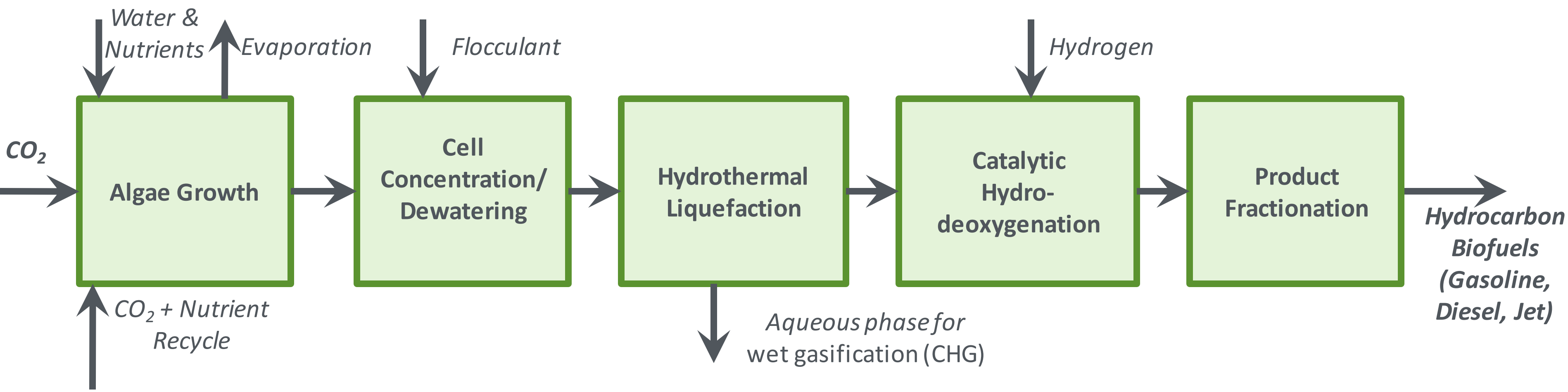
Biomass is rapidly heated in a fluidized bed reactor containing a catalyst to yield a partially stabilized and deoxygenated bio-oil vapor. The vapor is condensed into a liquid bio-oil and subsequently upgraded to produce hydrocarbon biofuel blendstocks.

Algal Lipid Upgrading (ALU)



Lipids are extracted from wet algal biomass via high-pressure homogenization and a hexane solvent; the algal oil can then be hydrotreated to produce advanced hydrocarbon fuels.

Whole Algae Hydrothermal Liquefaction (AHTL)



Whole algae cells are treated with heat and pressure to create bio-oil that can be hydrotreated and converted to advanced hydrocarbon fuels.

Category I: Responses by Pathway

Technology Area	Pathway	Number of Responses
Thermochemical Conversion: Bio-Oils	Fast Pyrolysis and Upgrading	0
	Ex-Situ Catalytic Pyrolysis	1
	In-Situ Catalytic Pyrolysis	1
Biochemical Conversion	Biological Conversion of Sugars to Hydrocarbons	4
	Catalytic Upgrading of Sugars to Hydrocarbons	2
Algae	Whole Algae Hydrothermal Liquefaction (AHTL)	6
	Algal Lipid Extraction Upgrading to Hydrocarbons (ALU)	5
Thermochemical Conversion: Gasification	Syngas Upgrading to Hydrocarbons	6

Pathway TEA and Sustainability Coordination

HISTORY

- TEA is a long established tool used to assess technical progress. **Sustainability** has always been an **underlying theme.**
- Sustainability moves to the forefront with respect to TEA, and efforts were made to integrate the two to support more optimized designs:
  - 2011: sustainability discussed in detail in the MYPP
  - 2012: began to identify appropriate indicators and metrics
  - 2013: all new design cases and SOT reports include section on sustainability, including metrics and sensitivity analysis

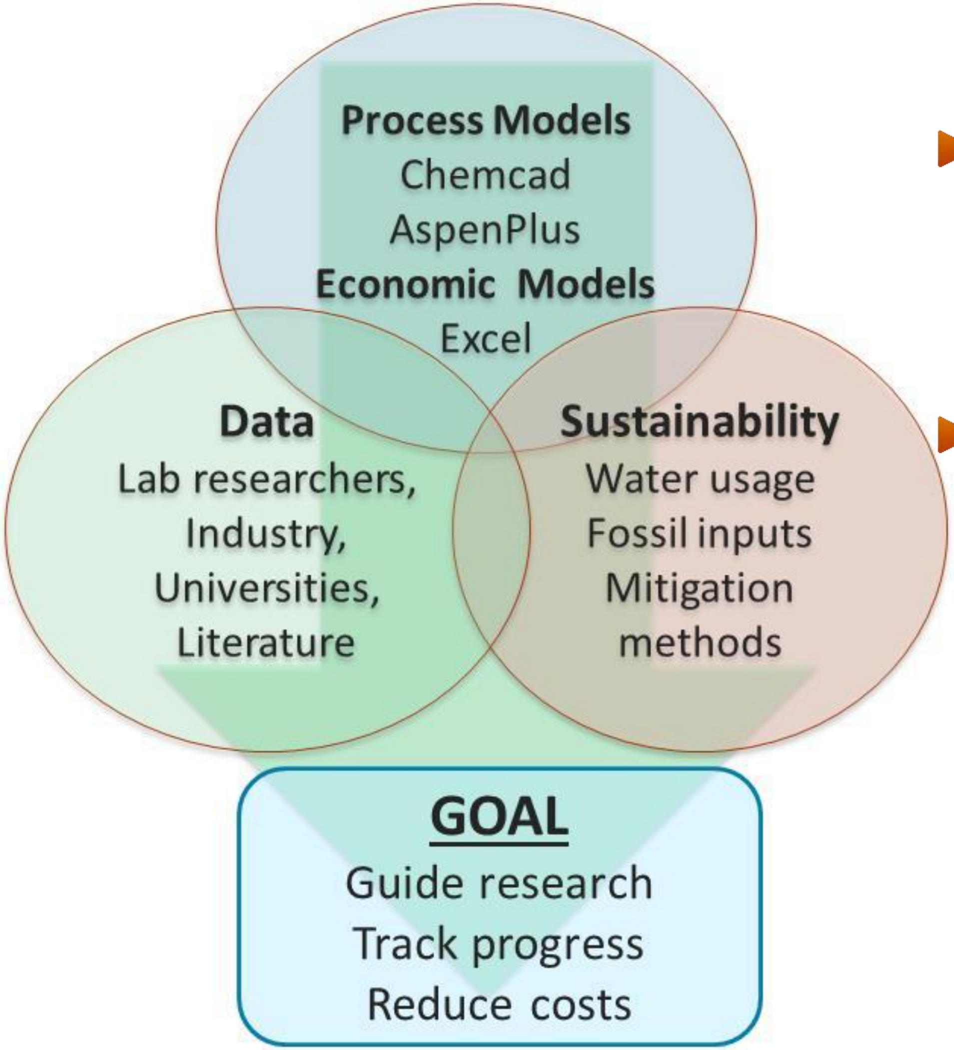
CONTEXT

- **Sustainable** and **economic** deployment of biofuel

OBJECTIVE

- **Combined TEA and environmental sustainability analysis** of emerging pathways helps to facilitate biorefinery designs that are economically feasible and minimally impactful to the environment.

Pathway TEA-Sustainability Coordination

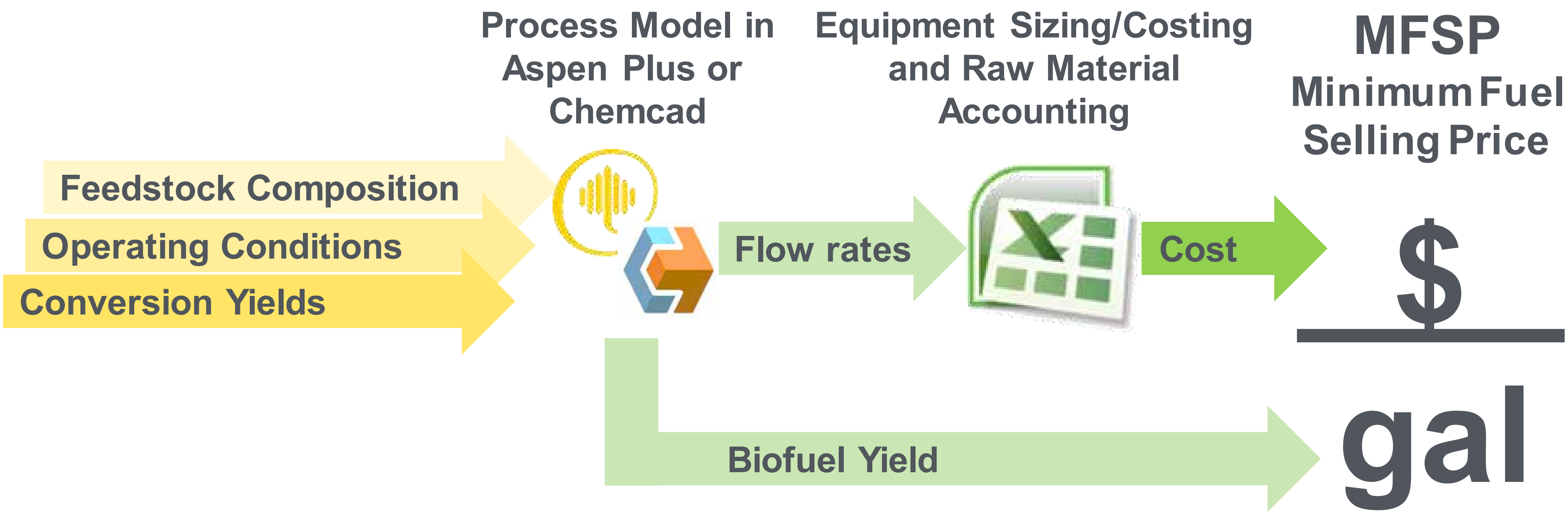


- **Approach** **Consistent** use of **BETO** technical, financial **assumptions;** set of defined sustainability **metrics**
- **Critical Success Factors**
  - Identify **cost reduction** strategies
  - Help **set research goals**
  - Quantify **sustainability impacts**
- **Potential Challenges – risk and uncertainty:**
  - **Sensitivity** studies to **identify** high **cost** and **sustainability impact** areas
  - Conclusion uncertainties **risk management**:
    - External peer review
    - Interaction with industry
    - Multi-lab collaborations
    - Make assumptions transparent

Background

- In March 2012, BETO formally initiated an effort to identify pathways to hydrocarbon fuels and intermediates
- In 2013, at the BETO Project Peer Review, BETO reported on this effort and unveiled eight representative pathways to hydrocarbon fuels chosen to help benchmark progress and guide R&D
- In May 2014, BETO issued a Request for Information seeking stakeholder input on Biofuel Pathways

Approach to Techno-Economic Analysis



- Modeling is rigorous and detailed with transparent assumptions
- Assumes nth-plant equipment costs
- Discounted cash-flow ROR calculation includes return on investment, equity payback, and taxes
- Determines the minimum selling price required for zero NPV

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