BIOMASS PROGRAM

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

Technology Pathway Selection Effort

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Techno-Economic Analysis

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- Setting R&D priorities
- Benchmarking
- Informing multi-sectoral analytical activities
- Track Program R&D progress against goals
- Identify technology process routes and prioritize funding
- Program direction decisions:
    - Are we spending our money on the right technology pathways?
    - Within a pathway: Are we focusing our funding on the highest priority activities?

Terminology and Concepts

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- Nth plant economics
  - Costs represent the case where several biorefineries with this technology have been built, which assumes lower contingency and other cost escalation factors
  - Assumes no risk premiums, no early-stage R&D, or start-up costs
- Pioneer plant
  - Costs represent a first-of-a-kind construction, where added cost factors are included for contingency and risk
  - Most closely represented by IBR projects
  - Few estimates available in the public domain
- Design Case:
  - Detailed, peer reviewed process simulation based on ASPEN or Chemcad
  - Establishes cost of production at biorefinery boundary
  - Provides estimate of nth plant capital and operating costs
  - Based on best available information at date of design case
  - Scope: feedstock cost, feedstock logistics, conversion cost, profit for biorefinery
  - Excludes: taxes, distribution costs, tax credits or other incentives

Introduction

- R&D targets for cellulosic ethanol achieved in 2012
  - Technical targets met corresponding to a MESP $2.05 (thermochem) and $2.15 (biochem)
  - Validated with integrated pilot at NREL
- In March 2012, initiated effort to select new pathways to hydrocarbon fuels and intermediates
- Focus on full pathways – feedstock to end product

Pathway Selection Process

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

July 2012
8 pathways selected from original 13

October 2012
Pathways prioritized and timeline for analysis developed

September 2013
Full design cases completed for 4 pathways (Fermentation of Lignocellulosic Sugars, ALU, AHTL, Fast Pyrolysis)

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

March 2013
Preliminary cost goals published in MYPP and key areas of research identified

September 2014
Year-by-year targets completed for 2013 pathways. Full design cases completed for 4 additional pathways (ex situ and in situ Catalytic Pyrolysis, Catalytic Upgrading of Lignocellulosic Sugars, Syngas to Hydrocarbons).

Criteria for downselect included:

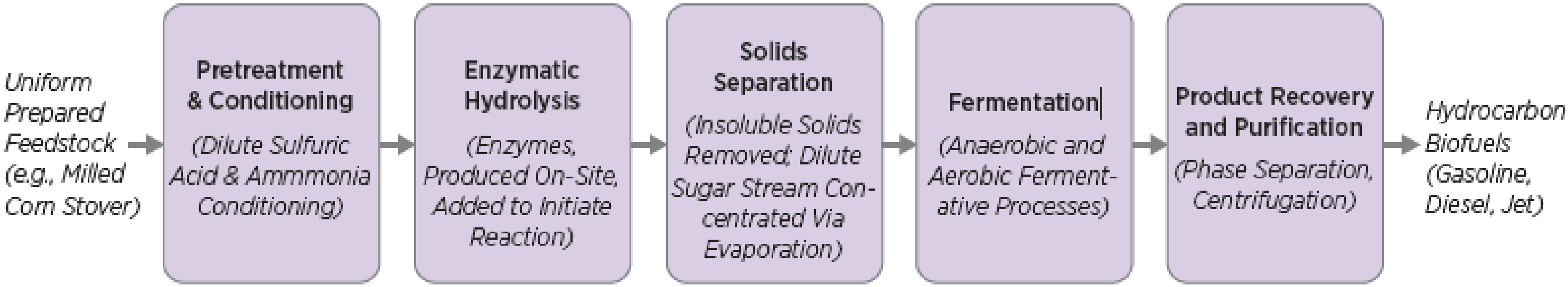
- Feasibility of achieving programmatic cost goal of $3/gal
- Near/Mid/Long-term techno-economic potential
- Potential national impact
- Feedstock availability/flexibility
- Data availability across the full pathway
- Co-product economics
- Potential volumetric impact in 2030
- Environmental Sustainability

Selected Pathways

- Fermentation of Sugars to Hydrocarbons
- Catalytic Upgrading of Sugars to Hydrocarbons
- Fast Pyrolysis*
- Ex-Situ Catalytic Pyrolysis
- In-Situ Catalytic Pyrolysis
- Whole Algae Hydrothermal Liquefaction (AHTL)
- Algal Lipid Upgrading (ALU)
- Syngas Upgrading to Hydrocarbon Fuels

* Update to the current design case

Fermentation of Sugars to Hydrocarbons

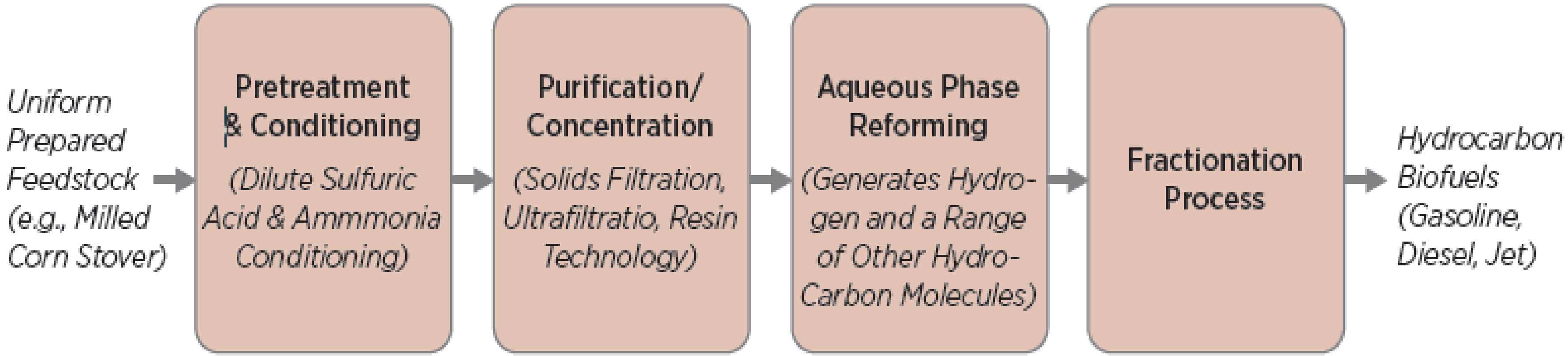


Biomass-derived sugars—separated from feedstocks through a series of chemical and biochemical processes—are further transformed, recovered, and purified to yield hydrocarbons for fuels and co-product commodities.

Rationale for Selecting Pathway

- Better utilization of biomass derived carbon sources (higher yields)
- Path to 2017 cost targets achievable via reasonable co-product credits
- Leverage previous front-end modeling and research through sugar production
- Back-integration and lessons-learned from IBR projects hasten process development

Catalytic Upgrading of Sugars to Hydrocarbons



Biomass-derived sugars—separated from feedstock through a series of chemical and biochemical processes—are upgraded via aqueous phase reforming into hydrocarbons for fuels and co-product commodities.

Rationale for Selecting Pathway

- Better utilization of biomass derived carbon sources (higher yields)
- Path to 2017 cost targets achievable with reasonable co-product credits
- Leverage previous front-end modeling and research through sugar production
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Algal Lipid Upgrading (ALU)

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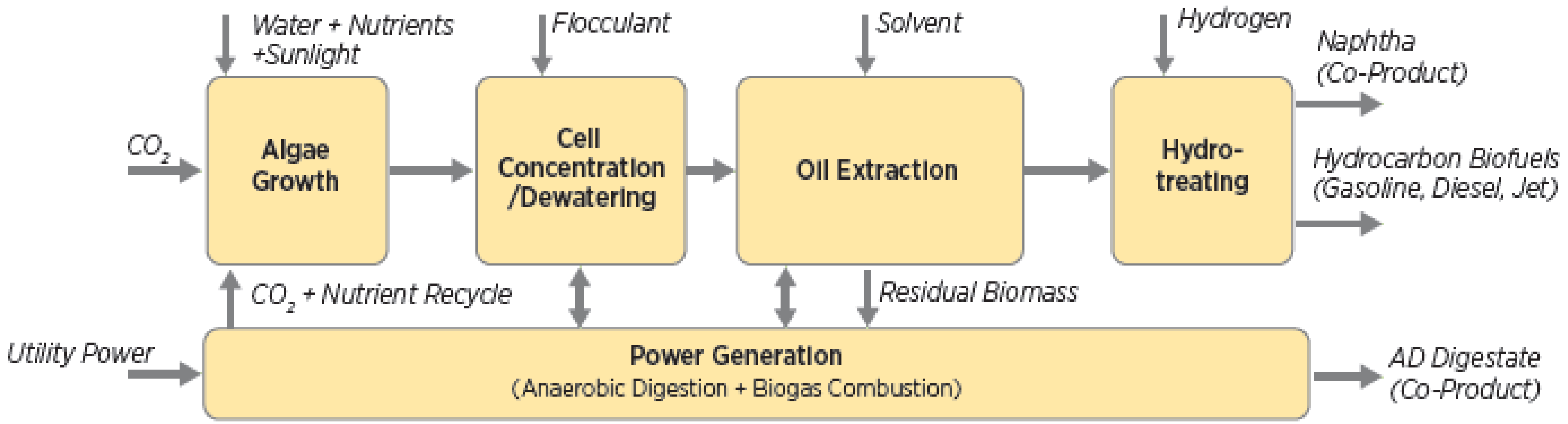
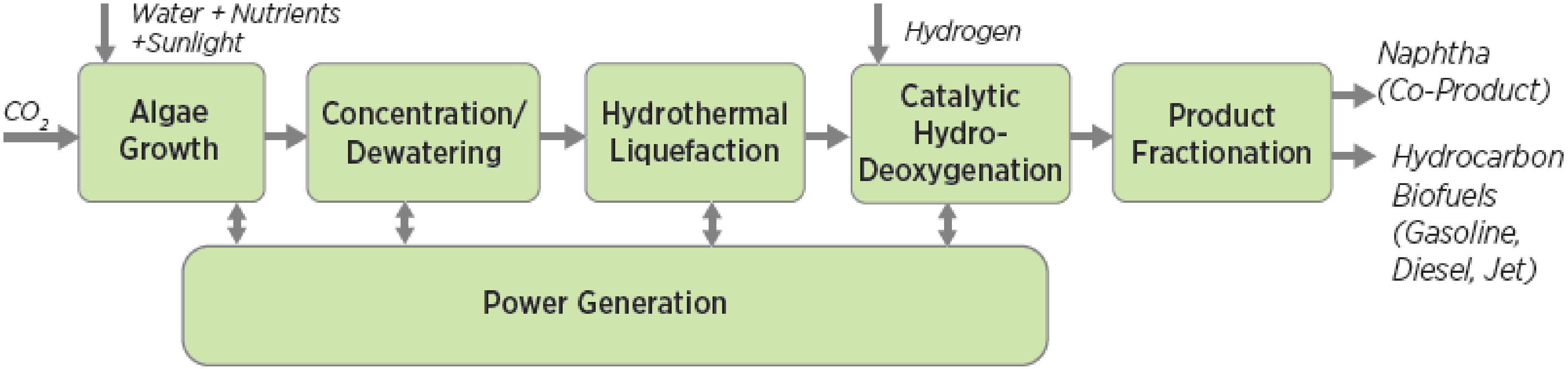


Bio-oil is extracted from algal biomass via high-pressure homogenization and a hexane solvent; the algal oil can then be hydrotreated to produce advanced hydrocarbon fuels.

<u>Rationale for Selecting Pathway</u>

- Raw algal oil intermediate is expected to require relatively mild upgrading (hydrotreating) to finished fuels at marginal cost
- Algal biomass can be tailored to produce specific components for fuel and/or product markets (potential for high-value coproducts)
- Nutrient recycle and heat and power integration through anaerobic digestion improves process economics and sustainability profile

Whole Algae Hydrothermal Liquefaction (ABHTL)



Bio-oils are separated from water via heat and pressure, so they can be catalytically hydrotreated and converted to advanced hydrocarbon fuels.

<u>Rationale for Selecting Pathway</u>

- HTL both extraction and conversion process (50-70% of carbon captured)
- Higher yield than other known extractions
- HTL is wet process using only water, no drying or solvent recovery needed
- Oil phase lower in oxygen content and easy to upgrade to hydrocarbons
- CHG is faster, smaller, and more complete than Anaerobic Digestion (AD)
- Leverages NABC, NAABB, and new AOP work in FY13

Fast Pyrolysis and Upgrading and Hydroprocessing

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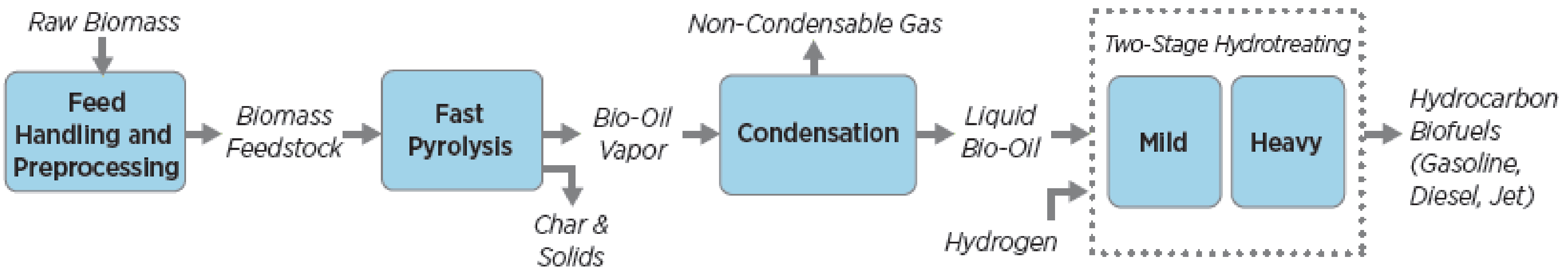
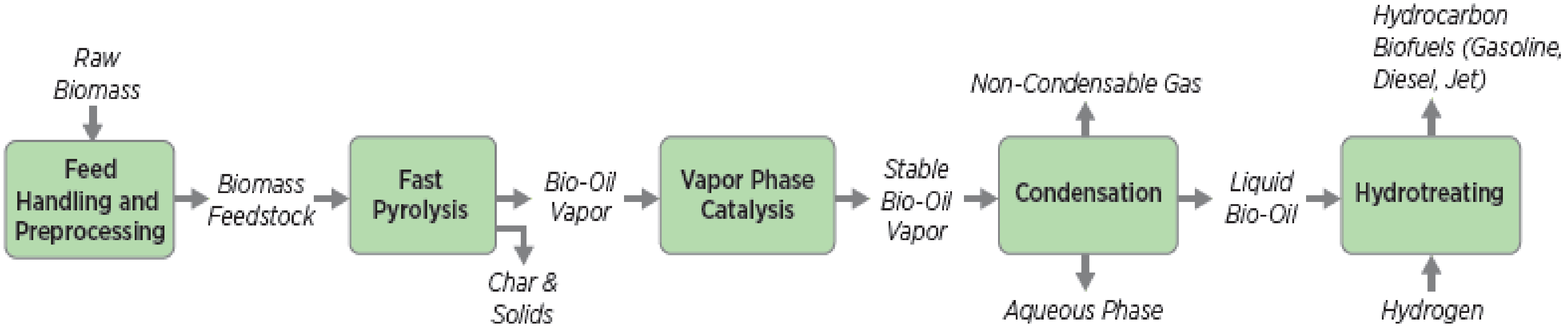


Biomass is rapidly heated in a fluidized bed reactor to yield vapors, which are condensed into a liquid bio-oil. This bio-oil is subsequently hydroprocessed to produce hydrocarbon biofuel blendstocks.

Rationale for Selecting Pathway

- Continuation of existing pathway

Ex-situ Catalytic Fast Pyrolysis

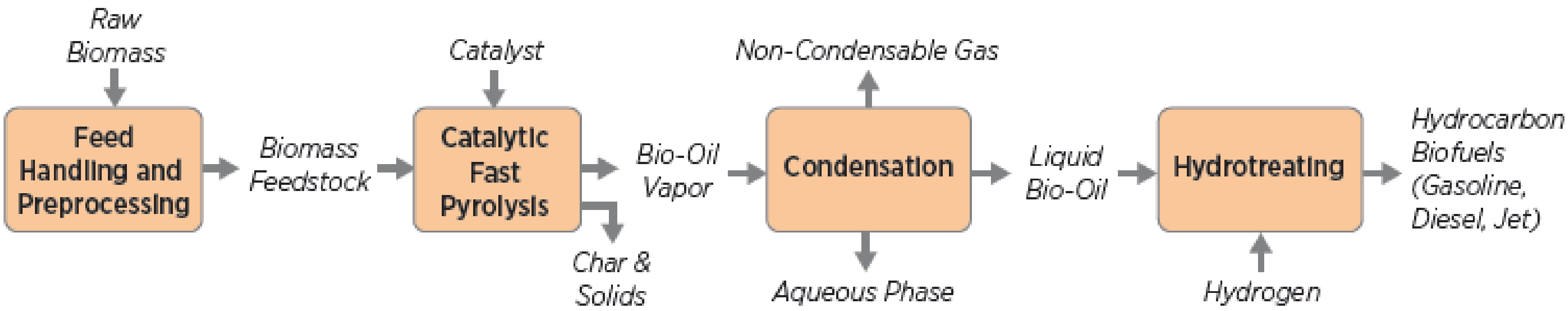


Biomass is rapidly heated in a fluidized bed reactor containing a catalyst to yield vapors, which are catalytically modified and condensed into a partially stabilized and deoxygenated liquid bio-oil. This stable bio-oil is subsequently upgraded to produce hydrocarbon biofuel blendstocks.

Rationale for Selecting Pathway

- Oil is lower in oxygen and likely easier to upgrade to hydrocarbons than fast pyrolysis derived bio-oil
- Greater control of gas/solid/liquid distribution as compared to fast pyrolysis
- May have a lower catalyst inventory
- Pathway R&D will facilitate upgrading step chemistry understanding and optimum catalyst/operating conditions

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.

Rationale for Selecting Pathway

- Requires only one liquefaction reactor and will have lower CapEX
- May have a lower OpEx if larger size feedstock particles are acceptable
- Oil is lower in oxygen and likely easier to upgrade to hydrocarbons than fast pyrolysis derived bio-oil
- Leverages ex-situ Catalytic Pyrolysis R&D upgrading step chemistry understanding and optimum catalyst/operating conditions

Syngas Upgrading to Hydrocarbon Fuels

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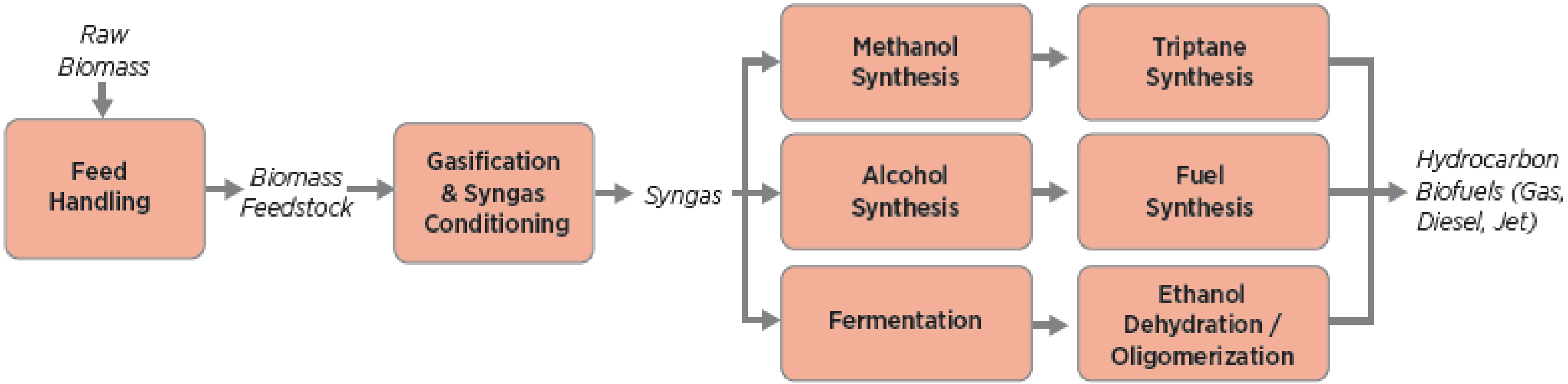

Biomass feedstocks are gasified to produce a clean syngas, which is used as a feedstock for hydrocarbon biofuel production.

Rationale for Selecting Pathway

- Exploits mixed alcohol synthesis catalysts advances, leverages existing work in gasification and syngas cleanup
- Opportunity to improve catalyst performance (selectivity, lifetime, coking) to enable higher hydrocarbon yields
- Process intensification opportunity

Next Steps

- Identify preliminary cost goals for each of the conversion pathways and determine key areas of research for each technology (2013)
- Set final cost goals and technical targets for each pathway (2013 – 2014)
- Publish design case reports for all pathways (2014 – 2015)
- Continue to explore new pathway options (ongoing)

Back-Up Slides

Pathways included in initial analysis

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Technology Area	Pathway
Sugars	Fermentation of Sugars to Hydrocarbons
	Catalytic Upgrading of Sugars to Hydrocarbons
	Fermentation of Sugars via Heterotrophic Algae to Hydrocarbons
Oils	Fast Pyrolysis and Upgrading
	Catalytic Pyrolysis – ex situ
	Catalytic Pyrolysis – in situ
	Hydropyrolysis
	Hydrothermal Liquefaction
	Solvent Liquefaction
Algae	Whole Algae Hydrothermal Liquefaction (ABHTL)
	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
	Gasification with Fermentation to Oxygenates
Other	Anaerobic digestion to CNG
	Anaerobic digestion to Hydrocarbons via GTL
	Coal Biomass to Liquids