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Charting a Path Forward:

New Pathways to Hydrocarbon Biofuels

May 22, 2013

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Bioenergy Technologies Office

Background

- Expanded scope of BETO portfolio to include hydrocarbon biofuels
- In September 2012, R&D targets for cellulosic ethanol were achieved
- In December 2011, a road mapping workshop on Conversion Technologies for Advanced Biofuels (CTAB) Workshop brought together representatives from national labs, industry and academia to identify critical areas of focus
- In March 2012, initiated effort to identify new pathways to hydrocarbon fuels and intermediates
  - Leveraged existing models and ongoing analysis at NREL, PNNL and NABC

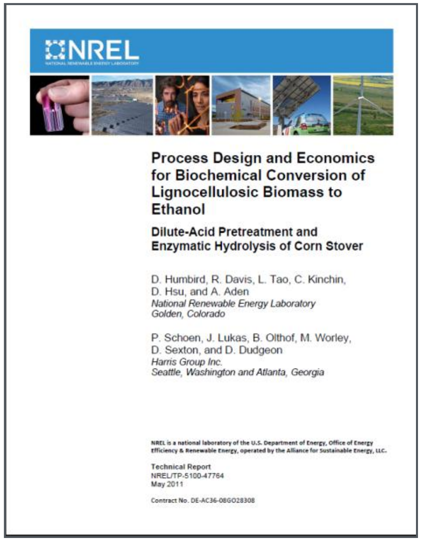
Techno-Economic Analysis (TEA)

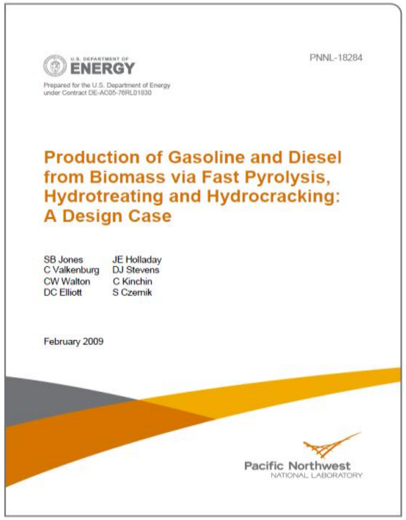
Purpose

- Setting R&D priorities
- Guiding program direction
- Identifying technology process routes and prioritize funding
- Benchmarking and tracking progress against goals
- Informing multi-sector analytical activities
- Providing a citable source for targets and budget justification

DOE ownership allows

- Control and transparency of assumptions
- Consistency among pathways for meaningful comparisons
- Open data


NREL
Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol
Dilute-Acid Pretreatment and Enzymatic Hydrolysis of Corn Stover
D. Humbird, R. Davis, L. Tao, C. Kinchin, D. Hsu, and A. Aden
National Renewable Energy Laboratory
Golden, Colorado
P. Schoen, J. Lukas, B. Olthof, M. Worley, D. Sexton, and D. Dudgeon
Harris Group Inc.
Seattle, Washington and Atlanta, Georgia
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.
Technical Report
NREL/TP-5100-47764
May 2011
Contract No. DE-AC36-08GO28308


U.S. DEPARTMENT OF ENERGY
PNNL-18284
Prepared for the U.S. Department of Energy under Contract DE-AC05-76RL01830
Production of Gasoline and Diesel from Biomass via Fast Pyrolysis, Hydrotreating and Hydrocracking: A Design Case
SB Jones, JE Holladay, C Valkenburg, DJ Stevens, CW Walton, C Kinchin, DC Elliott, S Czernik
February 2009
Pacific Northwest NATIONAL LABORATORY

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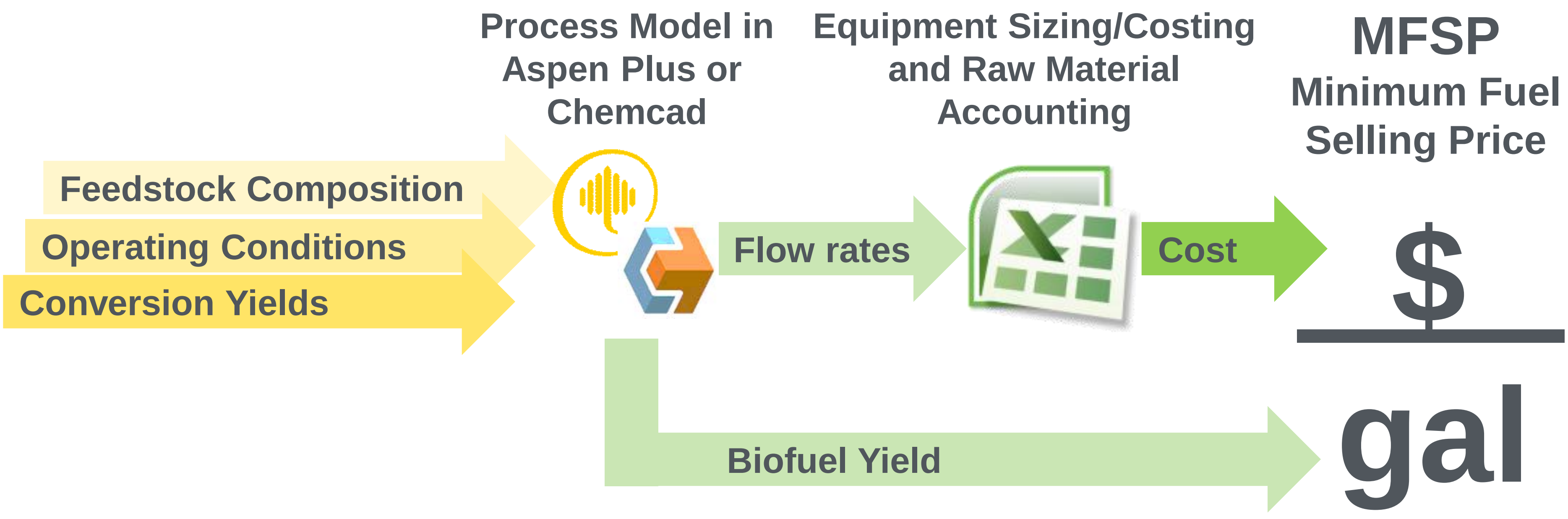
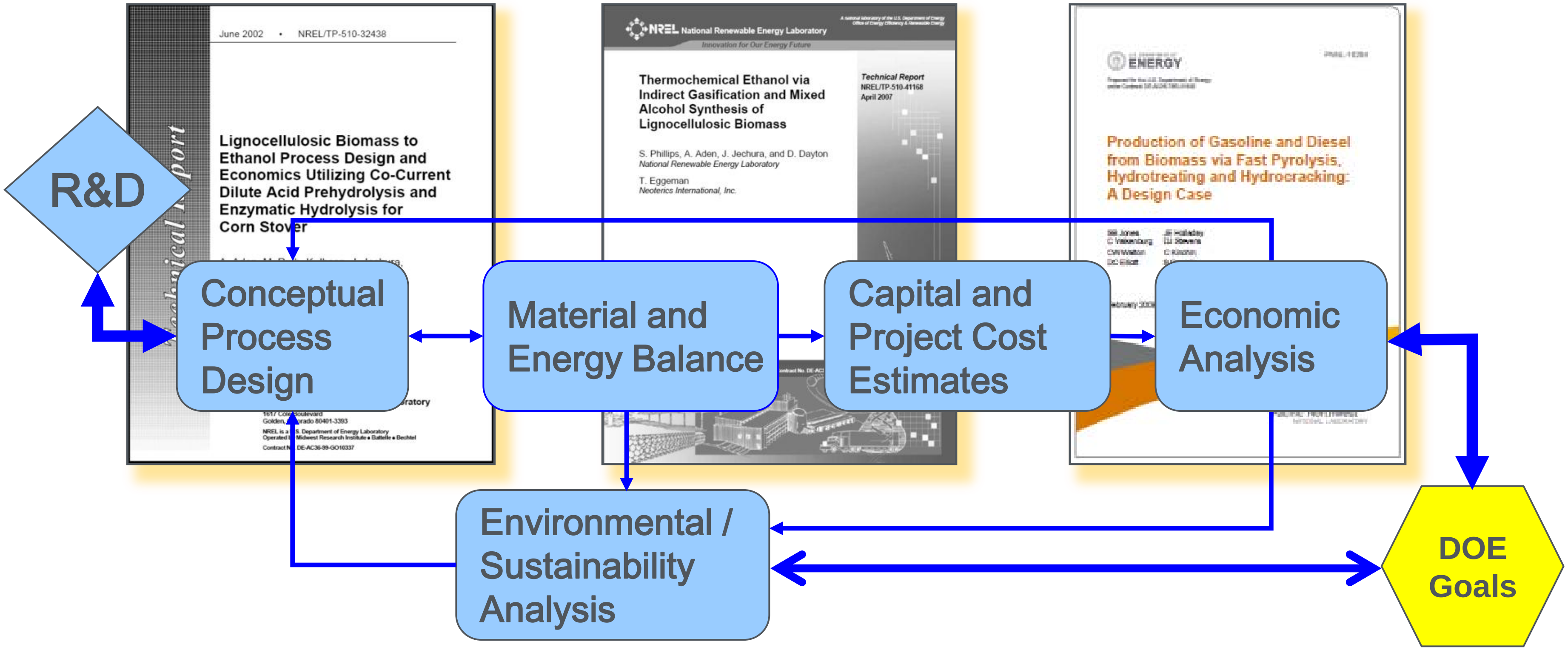
TEA Approach



- 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

TEA Approach



- Collaboration with engineering and construction firms to enhance credibility and quality
- Conceptual design reports are transparent, peer reviewed
- Iteration with researchers and experimentalists is crucial

Pathway Selection Process

March 2012
Working group convened, 18 potential pathways identified, 13 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 priority pathways selected from original 13

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

October 2012
Pathways prioritized and timeline for analysis developed

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

Criteria for evaluation 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

Pathways included in initial analysis

Technology Area	Pathway
Biochemical Conversion	Biological Conversion of Sugars to Hydrocarbons
	Catalytic Upgrading of Sugars to Hydrocarbons
	Fermentation of Sugars via Heterotrophic Algae to Hydrocarbons
Thermochemical Conversion: Bio-Oils	Fast Pyrolysis and Upgrading*
	Catalytic Pyrolysis – ex situ
	Catalytic Pyrolysis – in situ
	Hydropyrolysis
	Hydrothermal Liquefaction
Algae	Whole Algae Hydrothermal Liquefaction (AHTL)
	Algal Lipid Extraction Upgrading to Hydrocarbons (ALU)
Thermochemical Conversion: Gasification	Syngas Upgrading to Hydrocarbons
	Syngas Fermentation and Upgrading to Hydrocarbons
	Gasification with Fermentation to Oxygenates

* Update to the current design case

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Technology Pathways Technical Memos

- Technical memos published for 7 new technology pathways
- Provides process design details and identifies data gaps, uncertainties, and future research needs
- Starting point for developing joint NREL and PNNL design reports for hydrocarbon biofuels pathways in FY13 and FY14 for core platform tasks

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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 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

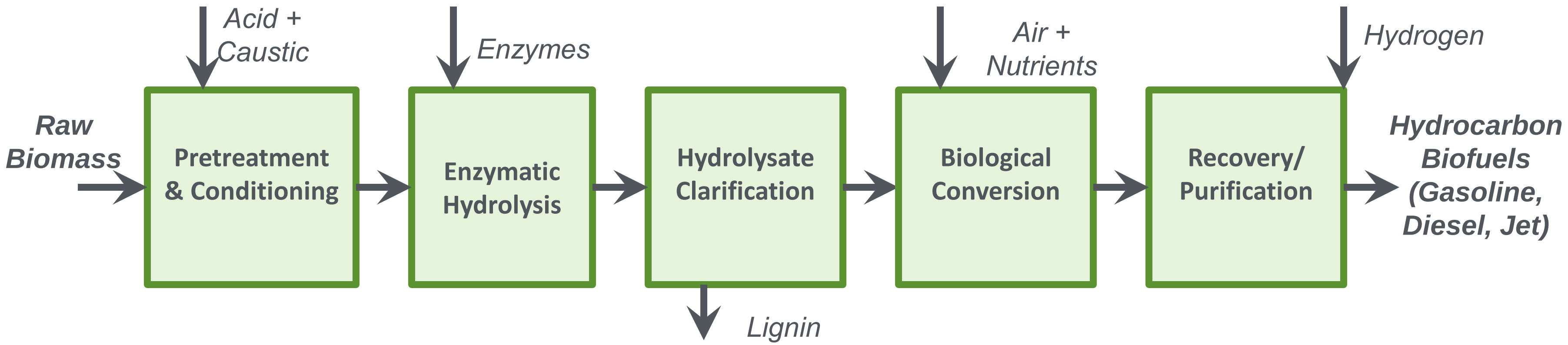
April 2013
Technical memos published for 7 new pathways to hydrocarbon biofuels

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 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

Biological Conversion of Sugars to Hydrocarbons

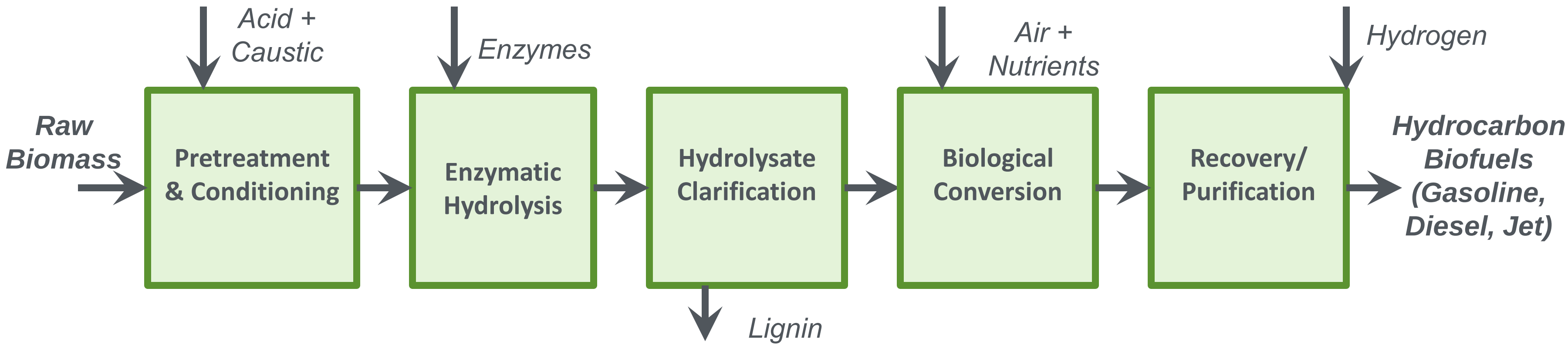


Biomass-derived sugars—separated from feedstocks through a series of chemical and biological processes—are further transformed, recovered, and purified to yield hydrocarbons for fuels and co-product commodities.

Rationale for Selecting Pathway

- Leverage experience from cellulosic ethanol pathway
- Microorganisms can be genetically engineered to produce targeted fuel components or co-products with high yields and value
- Increasing overall biomass utilization toward value added co-products can improve economic viability (i.e. lignin, acetate)

Biological Conversion of Sugars to Hydrocarbons



Data Gaps, Uncertainties, and Research Needs

- Maximize sugar (and/or carbon) utilization and microbe metabolic performance
- Improve tolerance of the microbes to lignocellulosic-derived sugar stream impurities
- Develop routes for lignin utilization and alternative co-product opportunities
- Investigate alternative pretreatment options and improved enzyme performance

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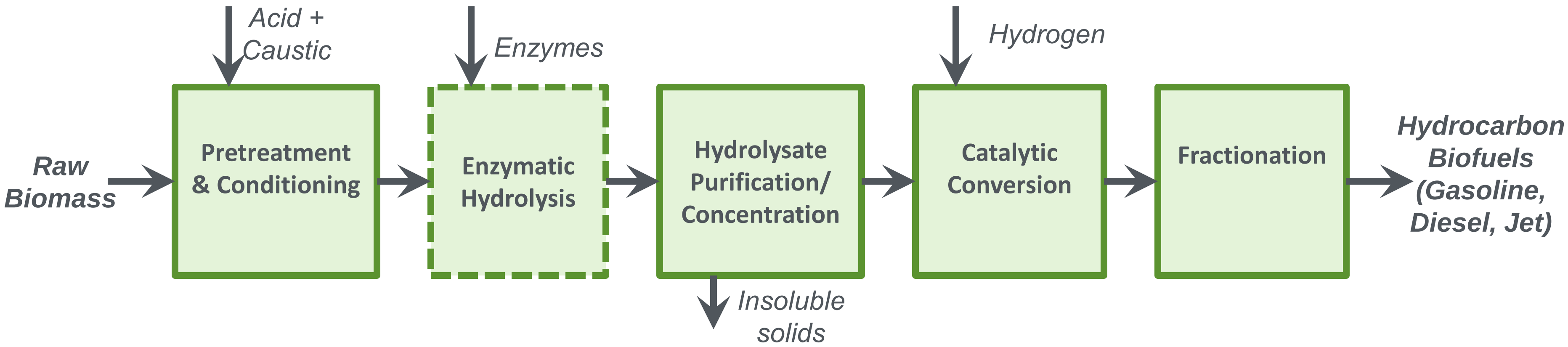
Catalytic Upgrading of Sugars to Hydrocarbons

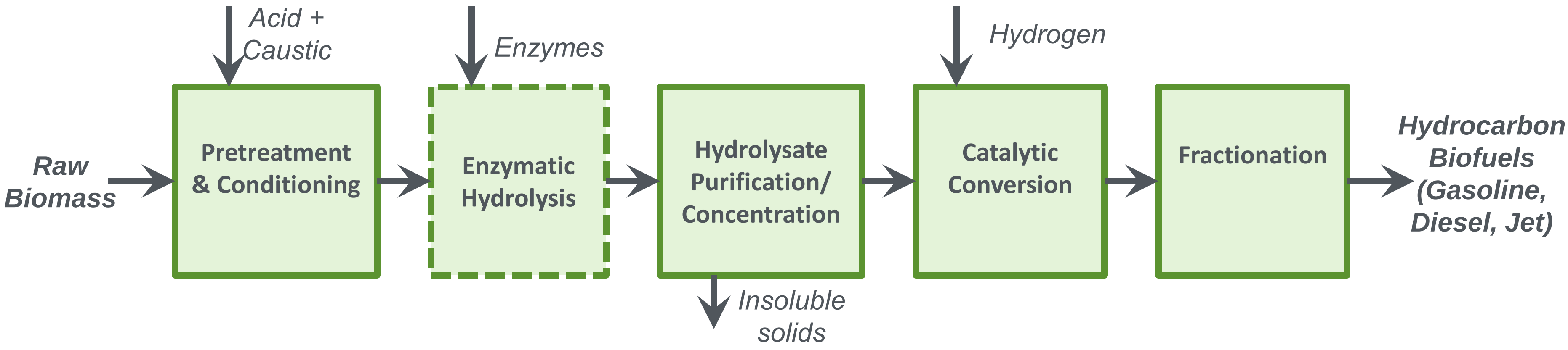


Biomass-derived sugars—separated from feedstock through a series of chemical and biochemical processes—are upgraded via aqueous phase reforming into hydrocarbons for fuels and co-product commodities.

Rationale for Selecting Pathway

- Leverage experience from cellulosic ethanol pathway
- Better utilization of biomass derived carbon sources (higher yields)
- Back-integration and lessons-learned from IBR projects hasten process development

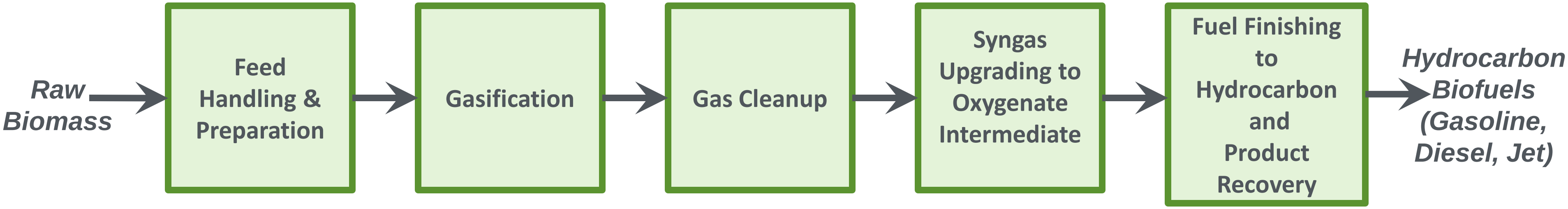
Catalytic Upgrading of Sugars to Hydrocarbons



Data Gaps, Uncertainties, and Research Needs

- Optimize upstream biomass deconstruction processes for downstream upgrading
- Maximize carbon selectivity towards desired fuel products
- Improve catalyst lifetime and durability
- Develop routes for lignin utilization and alternative co-product opportunities

Syngas Upgrading to Hydrocarbon Fuels

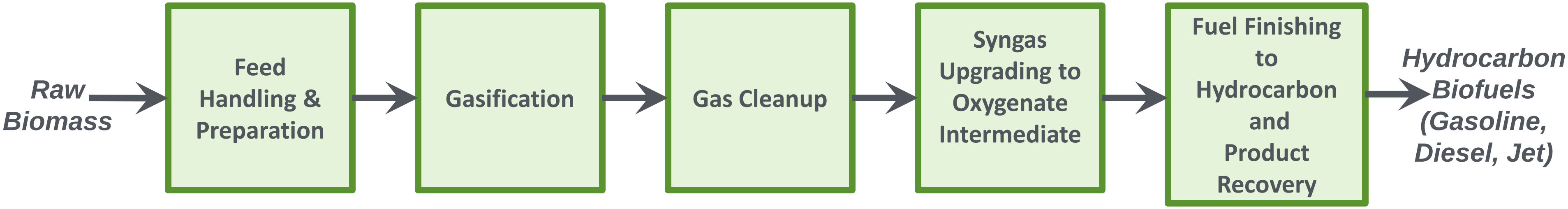


Biomass feedstocks are gasified to produce a clean syngas, which is used as a feedstock for hydrocarbon biofuel production.

Rationale for Selecting Pathway

- Leverage experience from cellulosic ethanol pathway
- Better utilization of biomass derived carbon sources (higher yields)
- Opportunity to improve catalyst performance (selectivity, lifetime, coking) to enable increased hydrocarbon yields
- Process intensification opportunity

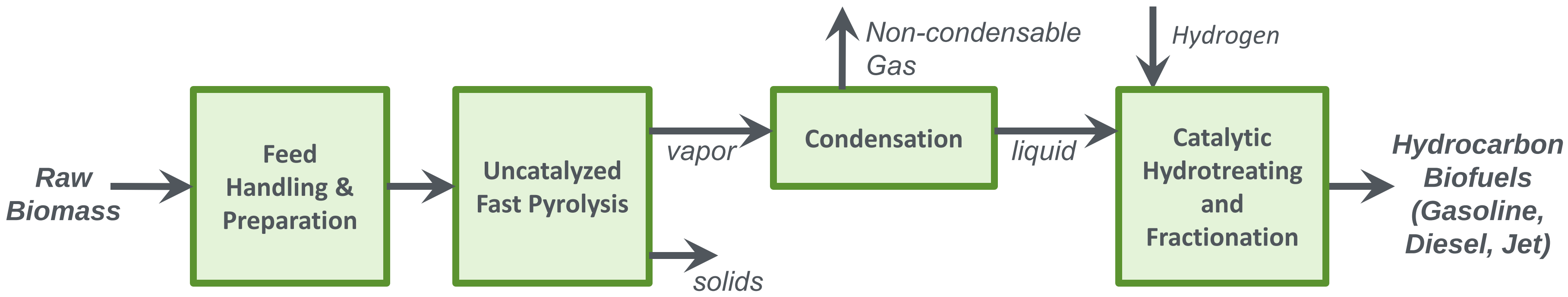
Syngas Upgrading to Hydrocarbon Fuels



Data Gaps, Uncertainties, and Research Needs

- Develop catalysts that maximize carbon selectivity to desired hydrocarbon products
- Improve catalyst life and stability
- Investigate alternative intermediates for hydrocarbon production
- Consolidate and optimize process configuration

Fast Pyrolysis and Upgrading and Hydroprocessing

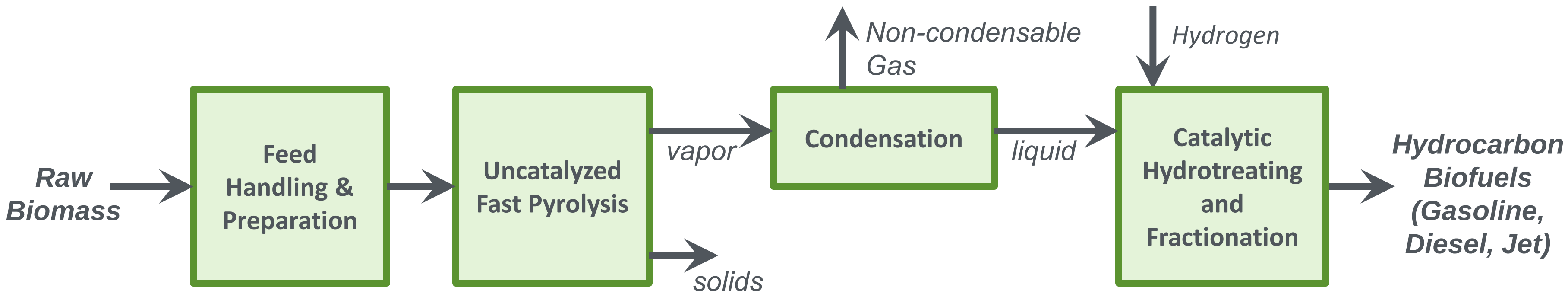


Biomass is rapidly heated in a fluidized bed reactor to yield vapors, which are condensed into a liquid bio-oil. This bio-oil is subsequently hydroprocessed to produce hydrocarbon biofuel blendstocks.

Rationale for Selecting Pathway

- Continuation of an existing pathway
- Fast pyrolysis is already commercial
- Upgrading produces hydrocarbons in good yield
- High probability of achieving programmatic cost target in 2017 timeframe

Fast Pyrolysis and Upgrading and Hydroprocessing



Data Gaps, Uncertainties, and Research Needs

- Increase hydrotreating catalyst life
- Reduce hydrotreating capital cost
- Demonstrate hydrocracking of the heavier than diesel cut
- Better characterization of fuel species and properties

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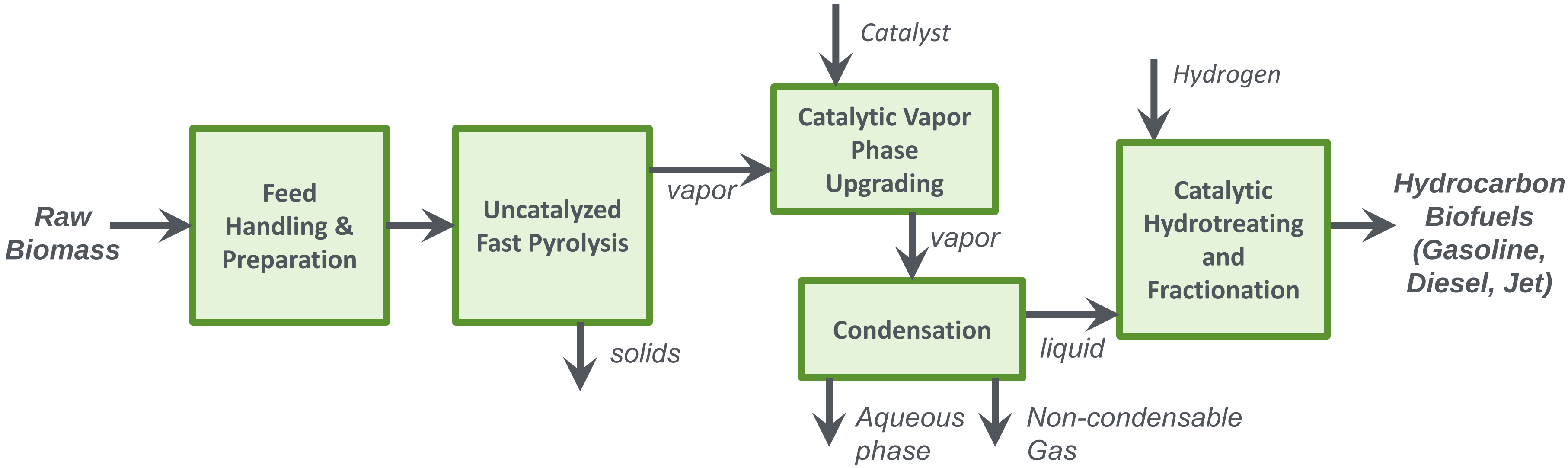
Ex situ Catalytic Fast Pyrolysis

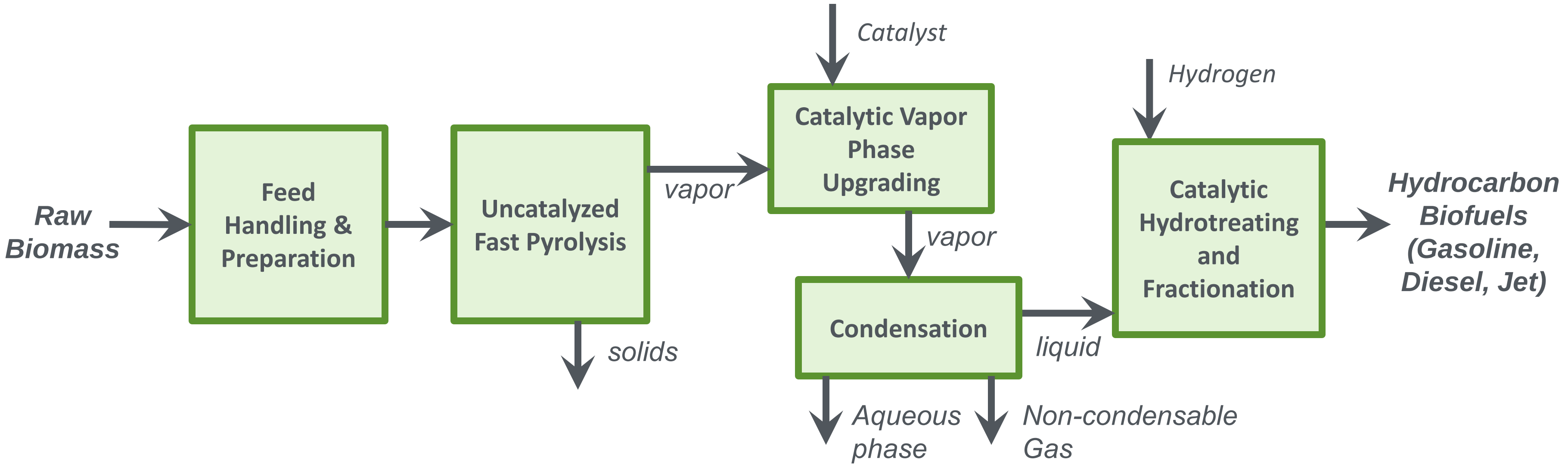


Biomass is rapidly heated in a fluidized bed reactor containing a catalyst to yield vapors, which are catalytically modified and condensed into a partially stabilized and deoxygenated liquid bio-oil. This stable bio-oil is subsequently upgraded to produce hydrocarbon biofuel blendstocks.

Rationale for Selecting Pathway

- Oil is lower in oxygen and likely easier to upgrade to hydrocarbons than fast pyrolysis derived bio-oil
- Vapor phase upgrading allows greater control of product distribution
- May have a lower catalyst inventory

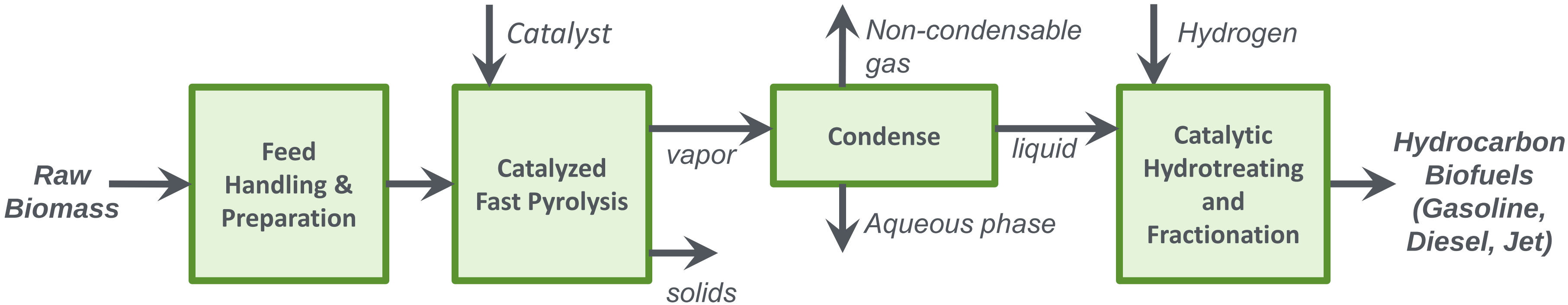
Ex situ Catalytic Fast Pyrolysis



Data Gaps, Uncertainties, and Research Needs

- Develop catalysts with improved yields, stability, and lifetimes
- Maximize overall conversion to desired hydrocarbon product
- Optimize VPU oil hydrotreating
- Develop economic wastewater treatments

In situ Catalytic Fast Pyrolysis

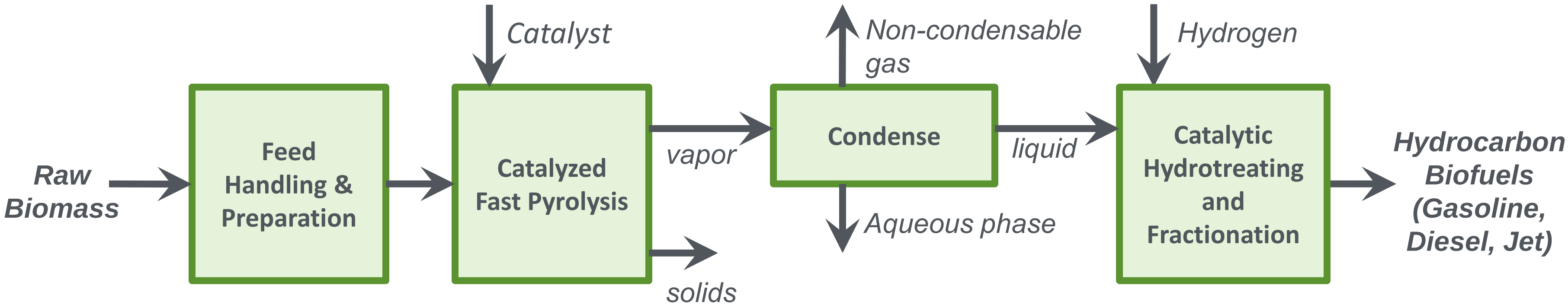


Biomass is rapidly heated in a fluidized bed reactor containing a catalyst to yield a partially stabilized and deoxygenated bio-oil vapor. The vapor is condensed into a liquid bio-oil and subsequently upgraded to produce hydrocarbon biofuel blendstocks.

Rationale for Selecting Pathway

- Oil is lower in oxygen and likely easier to upgrade to hydrocarbons than fast pyrolysis derived bio-oil
- Requires only one liquefaction reactor and may have lower CapEX
- May be able to leverage *ex situ* Catalytic Pyrolysis R&D upgrading chemistry

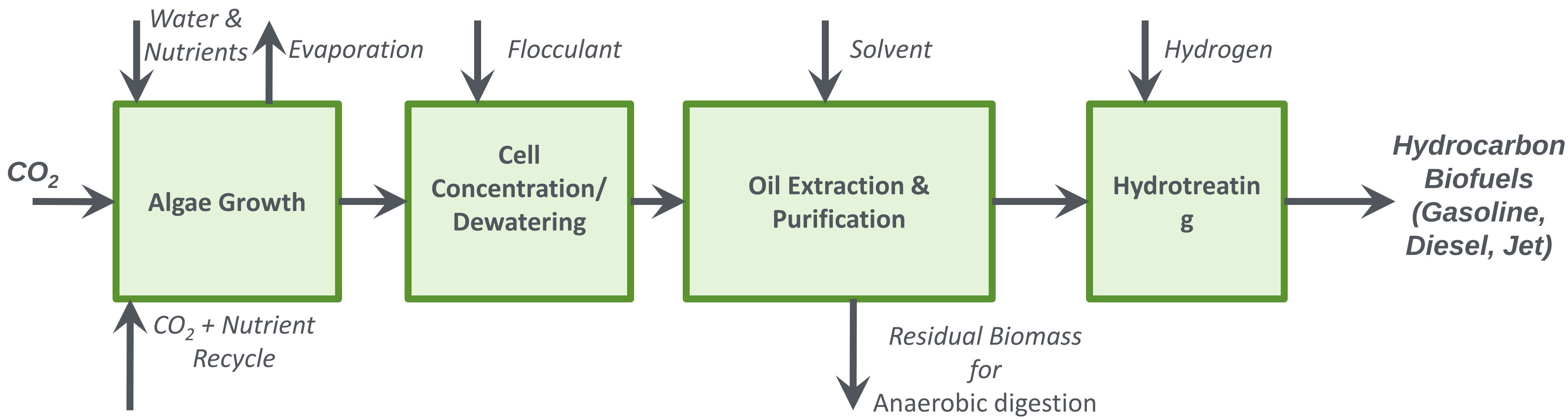
In situ Catalytic Fast Pyrolysis



Data Gaps, Uncertainties, and Research Needs

- Develop catalysts with improved yields, stability, and lifetimes
- Maximize overall conversion to desired hydrocarbon product
- Optimize oil hydrotreating
- Develop economic wastewater treatments

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.

Rationale for Selecting Pathway

- Raw algal oil intermediate is expected to require relatively mild upgrading 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

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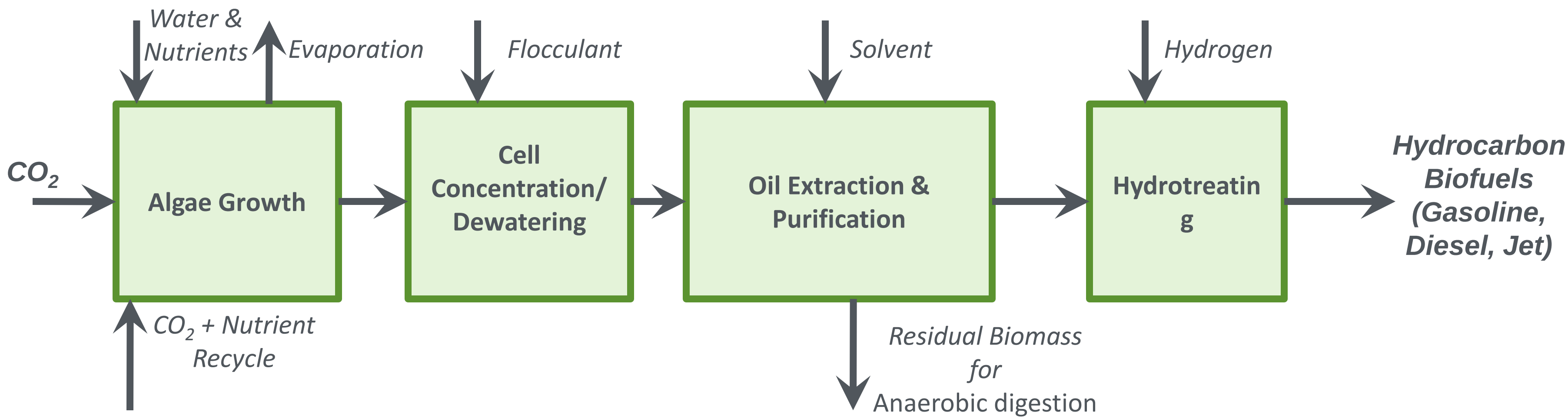
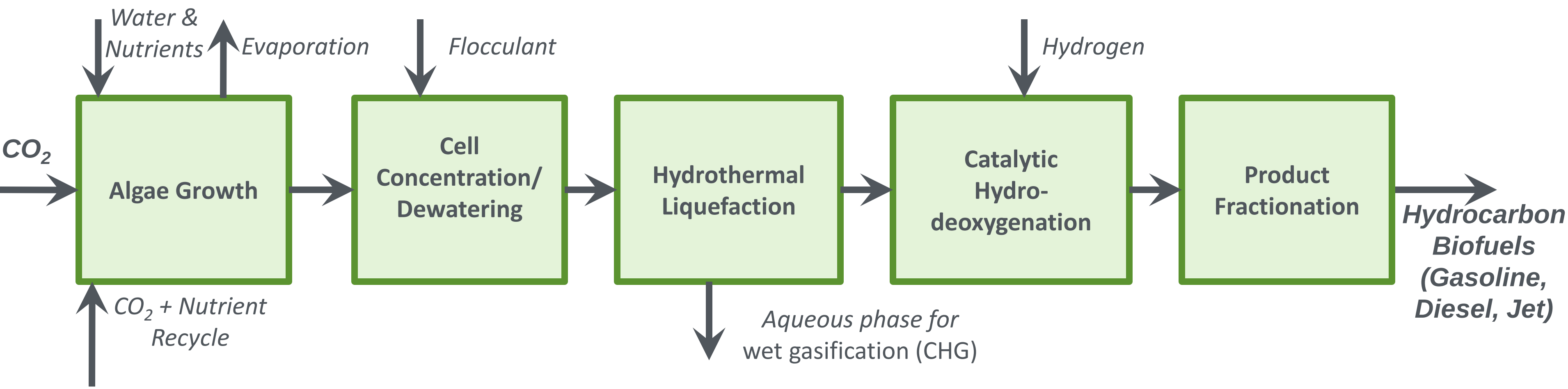
Algal Lipid Upgrading (ALU)



Data Gaps, Uncertainties, and Research Needs

- Enhance algal oil productivity on a sustained basis
- Improve algae dewatering and lipid extraction techniques and efficiencies at large scale
- Characterize the extracted algal oil and subsequent upgrading costs
- Evaluate co-product opportunities

Whole Algae Hydrothermal Liquefaction (AHTL)

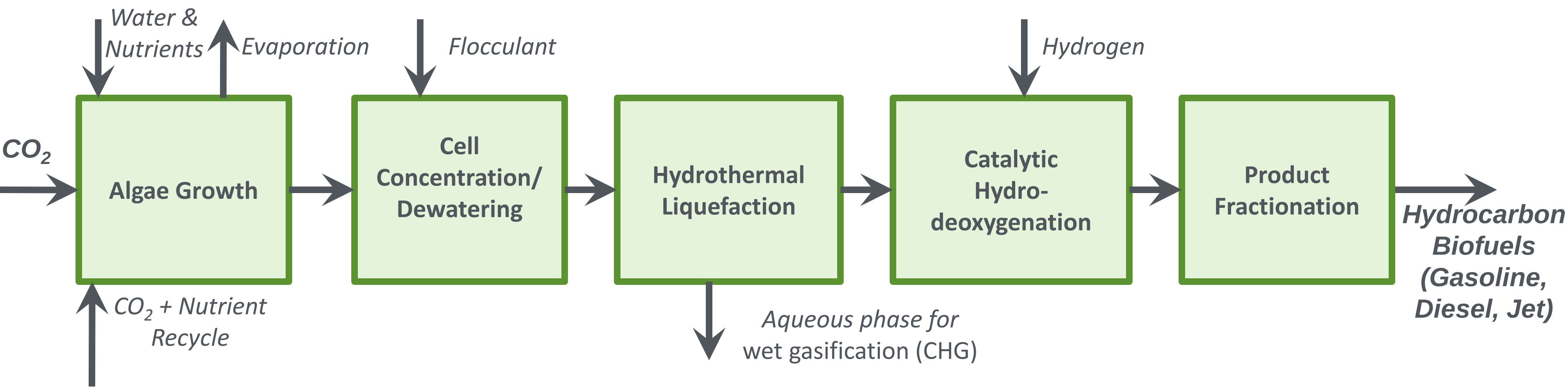


Whole algae cells are treated with heat and pressure to create bio-oil that can be hydrotreated and converted to advanced hydrocarbon fuels.

Rationale for Selecting Pathway

- HTL is both extraction and conversion process
- Higher yield than other extractions
- HTL is wet process using only water, no drying or solvent recovery needed
- Oil phase lower in oxygen content compared to pyrolysis oil
- Catalytic hydrothermal gasification (CHG) treats carbon-containing aqueous phase from HTL
- Leverages NABC and NAABB

Whole Algae Hydrothermal Liquefaction (AHTL)



Data Gaps, Uncertainties, and Research Needs

- Enhance algal biomass productivity on a sustained basis
- Optimize the nutrient recycle
- Demonstrate waste water treatment
- Characterize both AHTL oil and hydrocarbon products

Summary and Next Steps

- TEA is critical for guiding program direction, setting R&D priorities, and tracking progress towards goals
- Process for pathway selection was undertaken to identify new pathways to hydrocarbon fuels
- 8 pathways were selected with process design and key research needs detailed
- Effort leveraged ongoing work at NREL, PNNL, and NABC

Next Steps

- Set cost goals and technical targets for each priority pathway (2013 – 2014)
- Publish design case reports for all pathways (2014 – 2015)
- 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

Technical Memo Publications

Biddy, M.; Dutta, A.; Jones, S.; Meyer, A. 2013. Ex-Situ Catalytic Fast Pyrolysis Technology Pathway 9 pp.; NREL Report No. TP-5100-58050; PNNL-22317.
http://www.nrel.gov/docs/fy13osti/58050.pdf
http://www.pnl.gov/main/publications/external/technical_reports/PNNL-22317.pdf

Biddy, M.; Davis, R.; Jones, S. 2013. Whole Algae Hydrothermal Liquefaction Technology Pathway. 10 pp.; NREL Report No. TP-5100-58051; PNNL-22314.
http://www.nrel.gov/docs/fy13osti/58051.pdf
http://www.pnl.gov/main/publications/external/technical_reports/PNNL-22314.pdf

Biddy, M.; Dutta, A.; Jones, S.; Meyer, A. 2013. In-Situ Catalytic Fast Pyrolysis Technology Pathway. 9 pp.; NREL Report No. TP-5100-58056; PNNL-22320.
http://www.nrel.gov/docs/fy13osti/58056.pdf
http://www.pnl.gov/main/publications/external/technical_reports/PNNL-22320.pdf

Biddy, M.; Jones, S. 2013. Catalytic Upgrading of Sugars to Hydrocarbons Technology Pathway. 9 pp.; NREL Report No. TP-5100-58055; PNNL-22319.
http://www.nrel.gov/docs/fy13osti/58055.pdf
http://www.pnl.gov/main/publications/external/technical_reports/PNNL-22319.pdf

Technical Memo Publications

Davis, R.; Biddy, M.; Jones, S. 2013. Algal Lipid Extraction and Upgrading to Hydrocarbons Technology Pathway. 11 pp.; NREL Report No. TP-5100-58049; PNNL-22315
http://www.nrel.gov/docs/fy13osti/58049.pdf
http://www.pnl.gov/main/publications/external/technical_reports/PNNL-22315.pdf

Davis, R.; Biddy, M.; Tan, E.; Tao, L.; Jones, S. 2013. Biological Conversion of Sugars to Hydrocarbons Technology Pathway. 14 pp.; NREL Report No. TP-5100-58054; PNNL-22318.
http://www.nrel.gov/docs/fy13osti/58054.pdf
http://www.pnl.gov/main/publications/external/technical_reports/PNNL-22318.pdf

Talmadge, M.; Biddy, M.; Dutta, A.; Jones, S.; Meyer, A. 2013. Syngas Upgrading to Hydrocarbon Fuels Technology Pathway. 10 pp.; NREL Report No. TP-5100-58052; PNNL-22323.
http://www.nrel.gov/docs/fy13osti/58052.pdf
http://www.pnl.gov/main/publications/external/technical_reports/PNNL-22323.pdf

Design Report Publications

Dutta, A.; Talmadge, M.; Hensley, J.; Worley, M.; Dudgeon, D.; Barton, D.; Groendijk, P.; Ferrari, D.; Stears, B.; Searcy, E. M.; Wright, C. T.; Hess, J. R. (2011). Process Design and Economics for Conversion of Lignocellulosic Biomass to Ethanol: Thermochemical Pathway by Indirect Gasification and Mixed Alcohol Synthesis. 187 pp.; NREL Report No. TP-5100-51400. http://www.nrel.gov/docs/fy11osti/51400.pdf

Humbird, D.; Davis, R.; Tao, L.; Kinchin, C.; Hsu, D.; Aden, A.; Schoen, P.; Lukas, J.; Olthof, B.; Worley, M.; Sexton, D.; Dudgeon, D. (2011). Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol: Dilute-Acid Pretreatment and Enzymatic Hydrolysis of Corn Stover. 147 pp.; NREL Report No. TP-5100-47764. http://www.nrel.gov/docs/fy11osti/47764.pdf

Jones SB, C Valkenburg, CW Walton, DC Elliott, JE Holladay, DJ Stevens, C Kinchin, and S Czernik. (2009). Production of Gasoline and Diesel from Biomass via Fast Pyrolysis, Hydrotreating and Hydrocracking: A Design Case . PNNL-18284 Rev. 1. http://www.pnl.gov/main/publications/external/technical_reports/PNNL-18284rev1.pdf

Algae Harmonization Report

Davis, R.; Fishman, D.; Frank, E. D.; Wigmosta, M. S.; Aden, A.; Coleman, A. M.; Pienkos, P. T.; Skaggs, R. J.; Venteris, E. R.; Wang, M. Q. (2012). Renewable Diesel from Algal Lipids: An Integrated Baseline for Cost, Emissions, and Resource Potential from a Harmonized Model. 85 pp.; NREL Report No. TP-5100-55431; ANL/ESD/12-4; PNNL-21437. http://www.nrel.gov/docs/fy12osti/55431.pdf

Back-Up Slides

Pathways included in initial analysis

Technology Area	Pathway
Biochemical Conversion	Biological Conversion of Sugars to Hydrocarbons
	Catalytic Upgrading of Sugars to Hydrocarbons
	Fermentation of Sugars via Heterotrophic Algae to Hydrocarbons
Thermochemical Conversion: Bio-Oils	Fast Pyrolysis and Upgrading * Update to the current design case
	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)
Thermochemical Conversion: Gasification	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

Technology Pathways Development

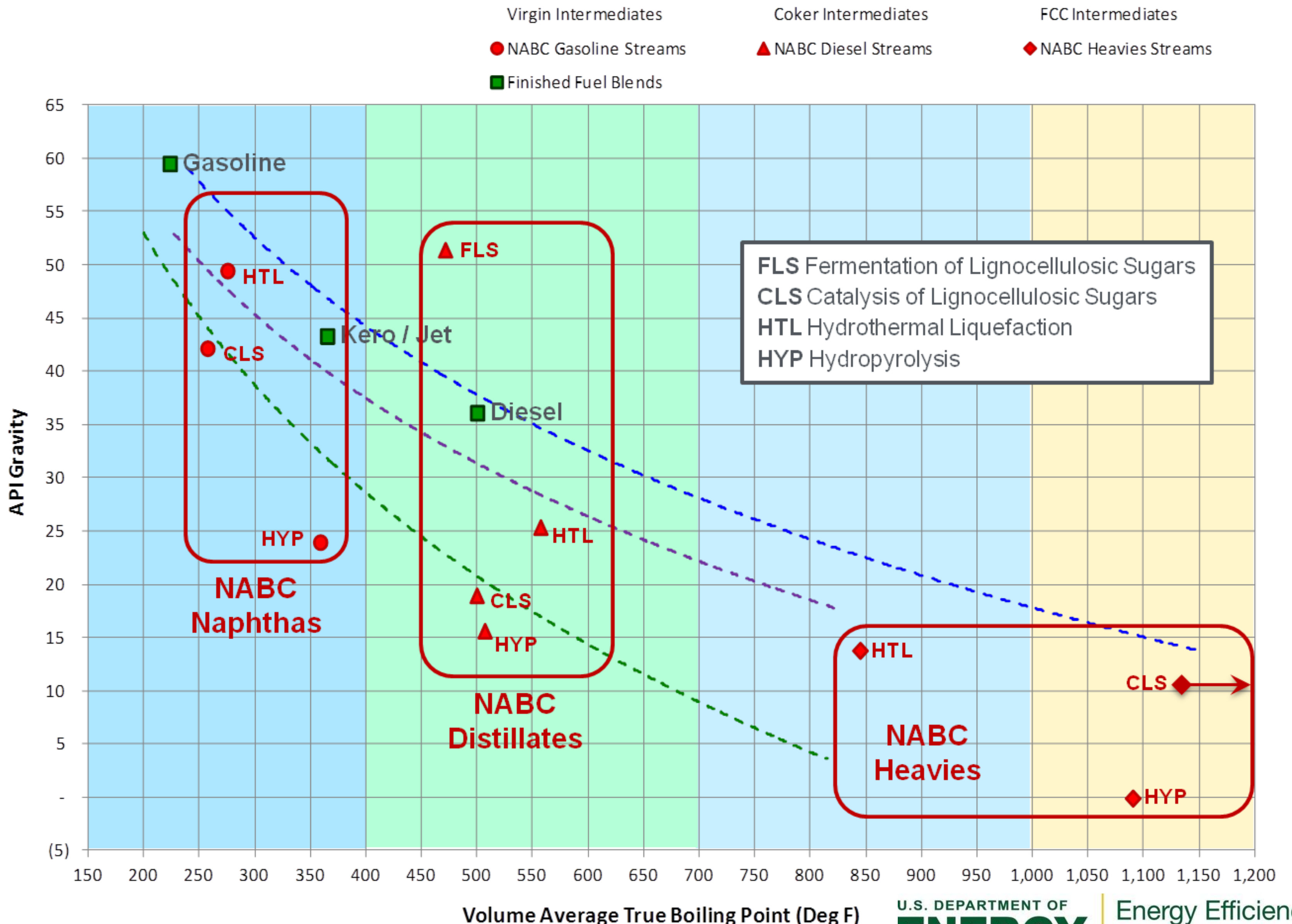
In 2012, eight technology pathways to hydrocarbon biofuels were selected based on the following criteria:

- Feasibility of achieving 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
- Environmental sustainability

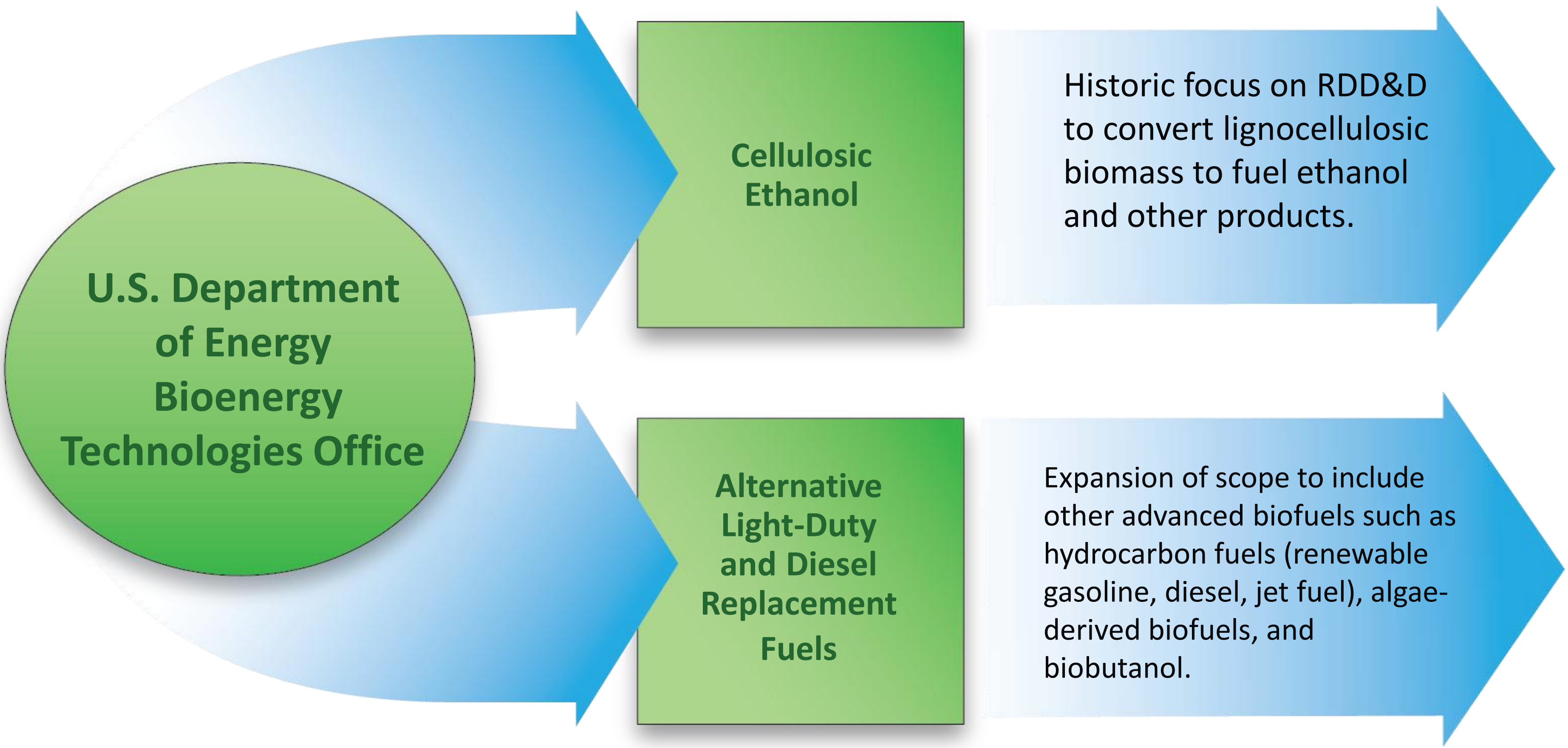
Technology Pathways
Biological Conversion of Sugars to Hydrocarbons
Catalytic Upgrading of Sugars to Hydrocarbons
Ex-situ Catalytic Pyrolysis
In-Situ Catalytic Pyrolysis
Fast Pyrolysis and Upgrading
Syngas to Mixed Alcohols to Hydrocarbons
Whole Algae Hydrothermal Liquefaction
Algal Lipid Extraction Upgrading to Hydrocarbons

Next Steps: Identify cost goals and technical targets and develop design case reports for each pathway

Intermediate / Product Comparison

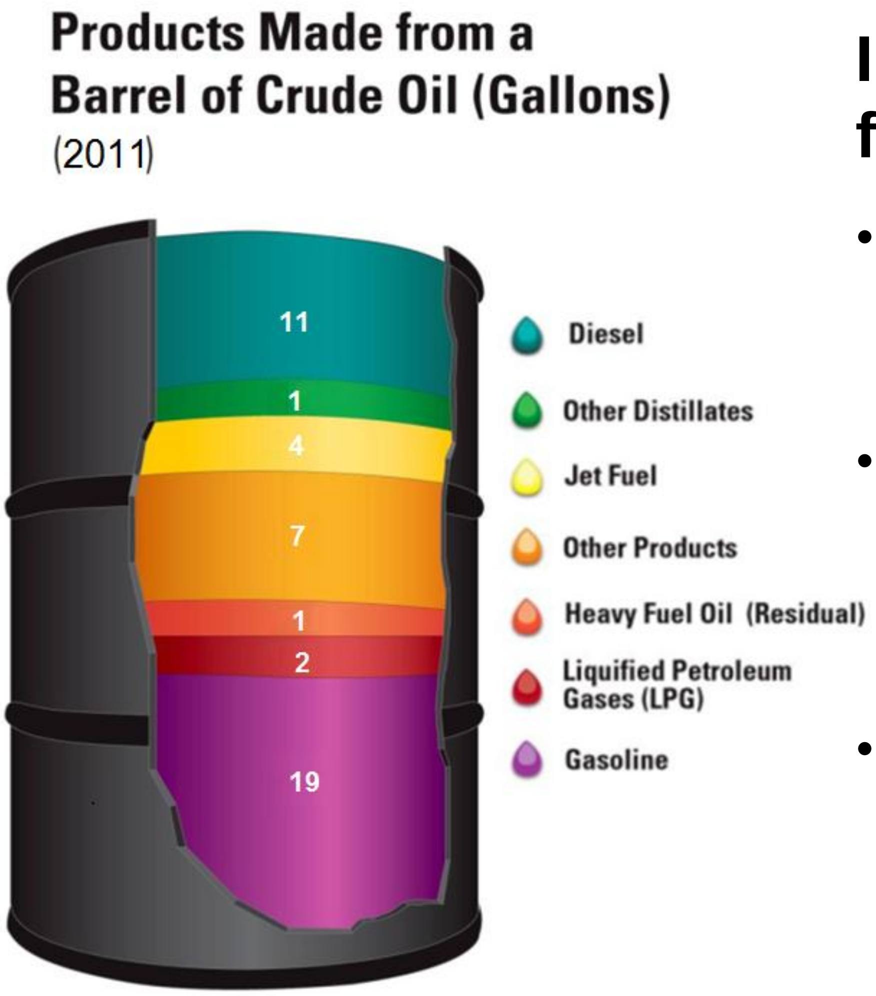


Expanding Scope



The Bioenergy Technologies Office forms cost-share partnerships with key stakeholders to develop, demonstrate, and deploy technologies for advanced biofuels, bioproducts, and biopower from lignocellulosic and algal biomass.

Current Strategic Focus: Replacing the Entire Barrel



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.

Current Strategic Focus: CTAB Workshop held 12/2011

Conversion Technologies for Advanced Biofuels (CTAB)

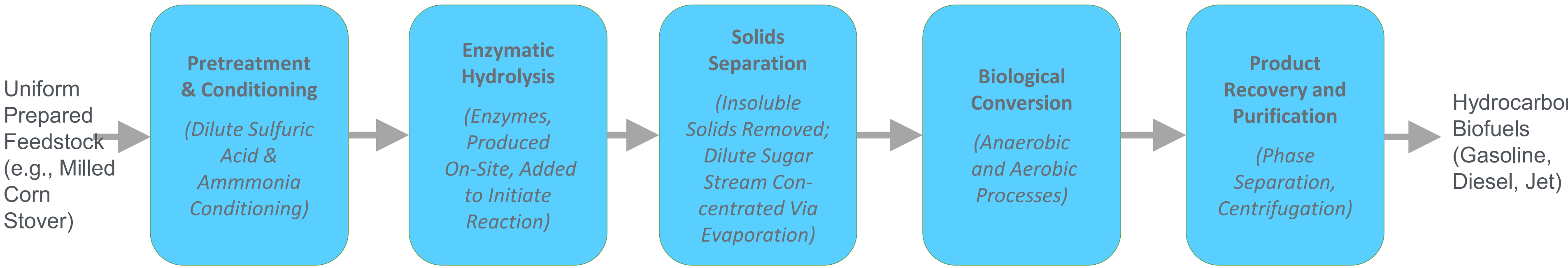
- Expand upon existing R&D roadmaps
  - *Update Breaking the Biological Barriers to Cellulosic Ethanol*
  - *Breaking the Chemical and Engineering Barriers to Lignocellulosic Biofuels)*
- **Areas of focus**: R&D Barriers and Activities - dedicated focus to hydrocarbon biofuels
- Gathered input from industry, 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

Terminology and Concepts

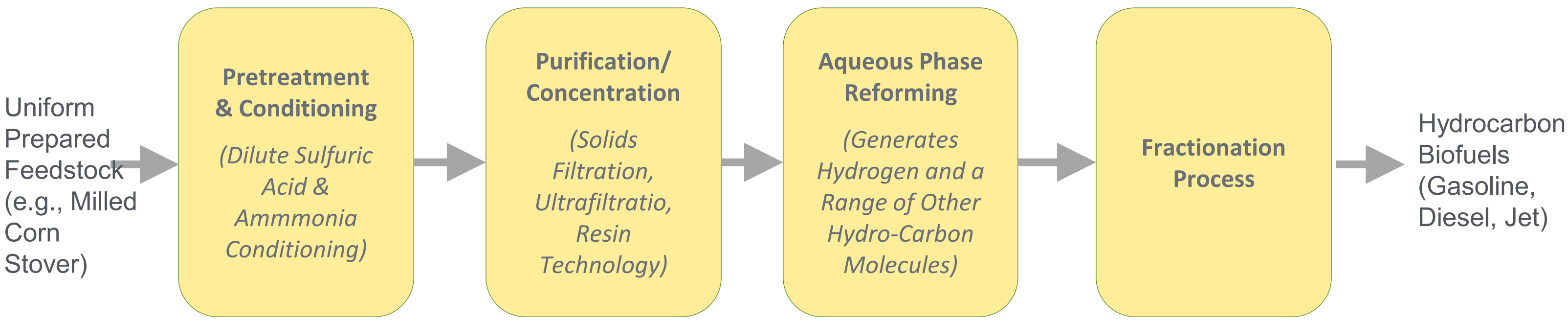
- Nth plant economics
  - Costs represent the case where several biorefineries with this technology have been built, which assumes lower contingency and other cost escalation factors
  - Assumes no risk premiums, no early-stage R&D, or start-up costs
- Pioneer plant
  - Costs represent a first-of-a-kind 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

Condensed Figures

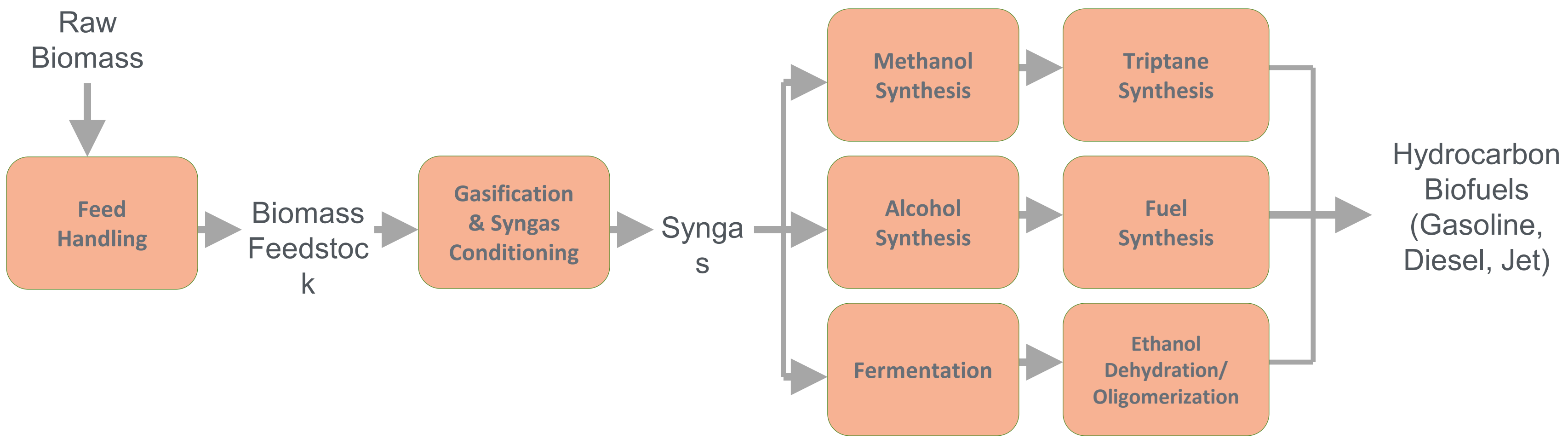
Biological Conversion



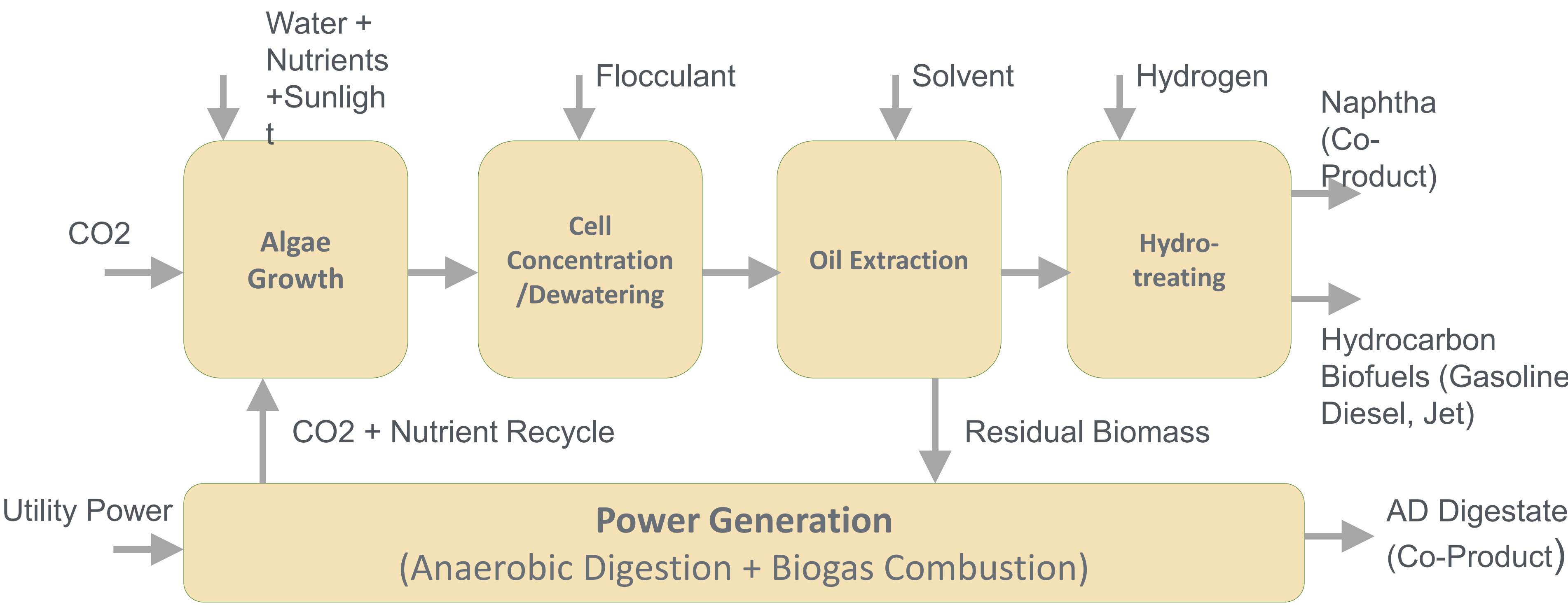
Catalytic Upgrading of Sugars



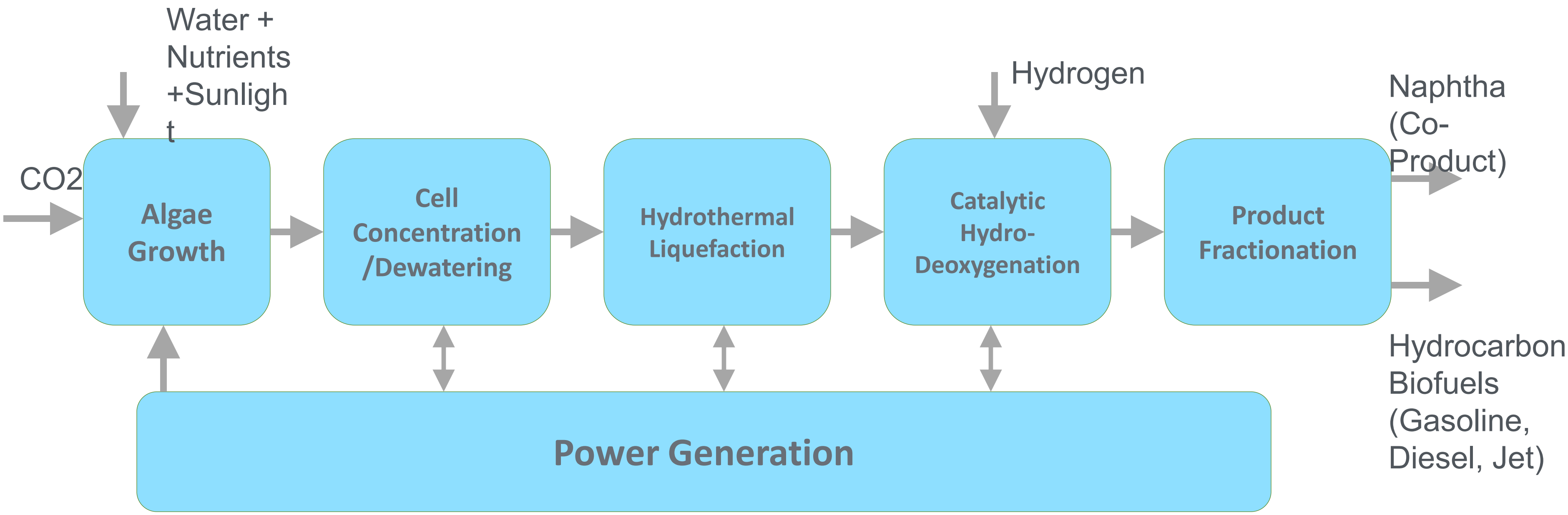
Syngas Upgrading



ALU

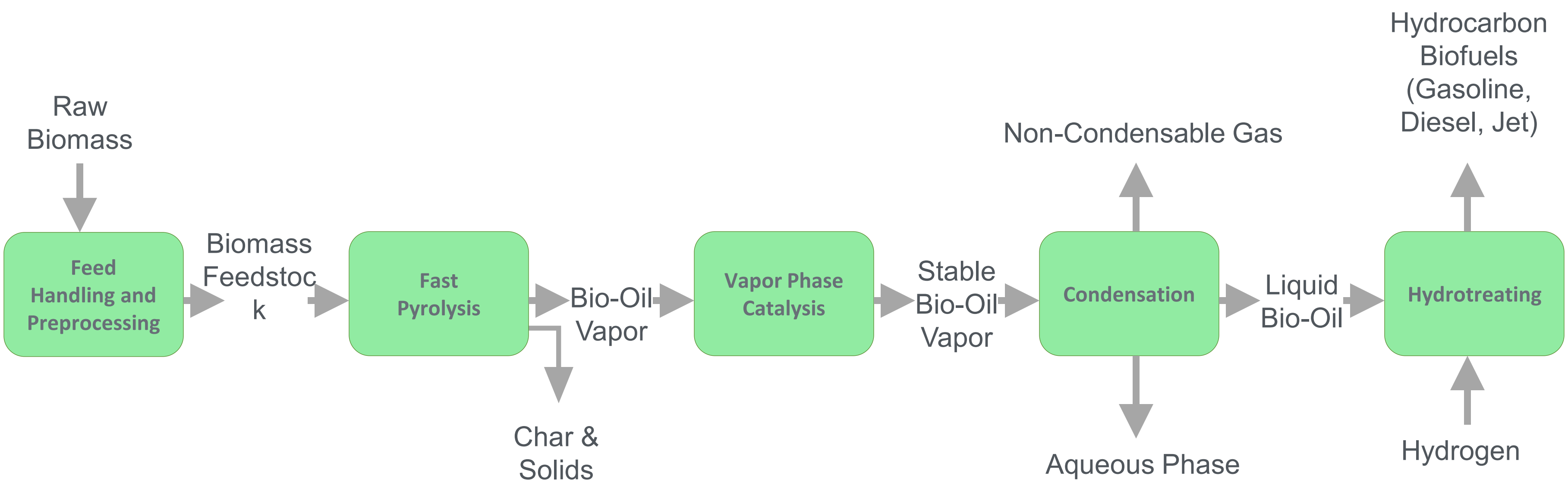

Water + Nutrients +Sunlight
Flocculant
Solvent
Hydrogen
Naphtha (Co-Product)
CO2
Algae Growth
Cell Concentration /Dewatering
Oil Extraction
Hydro-treating
Hydrocarbon Biofuels (Gasoline Diesel, Jet)
CO2 + Nutrient Recycle
Residual Biomass
Utility Power
Power Generation
(Anaerobic Digestion + Biogas Combustion)
AD Digestate (Co-Product)

AHTL

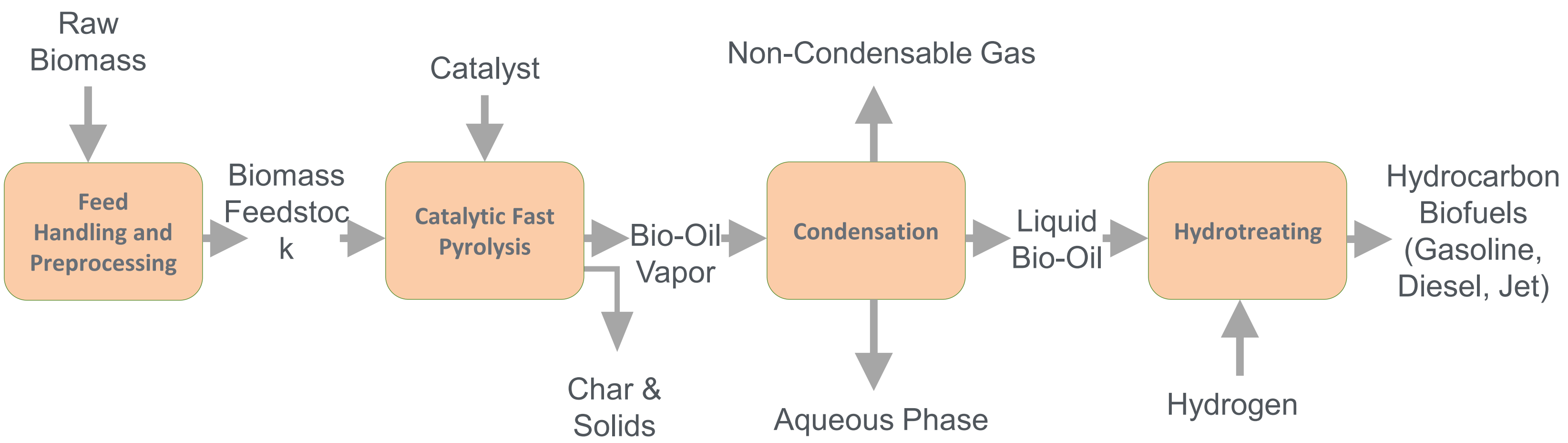


Water +
Nutrients
+Sunligh
t
Hydrogen
Naphtha
(Co-
Product)
CO2
Algae
Growth
Cell
Concentration
/Dewatering
Hydrothermal
Liquefaction
Catalytic
Hydro-
Deoxygenation
Product
Fractionation
Hydrocarbon
Biofuels
(Gasoline,
Diesel, Jet)
Power Generation

Fast Pyrolysis



In situ CFP



Raw Biomass
Feed Handling and Preprocessing
Biomass Feedstoc k
Catalyst
Catalytic Fast Pyrolysis
Char & Solids
Bio-Oil Vapor
Non-Condensable Gas
Condensation
Aqueous Phase
Liquid Bio-Oil
Hydrotreating
Hydrogen
Hydrocarbon Biofuels (Gasoline, Diesel, Jet)

Fast Pyrolysis