U.S. DEPARTMENT OF ENERGY
BIOMASS PROGRAM

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Pathways for Algal Biofuels

November 27, 2012

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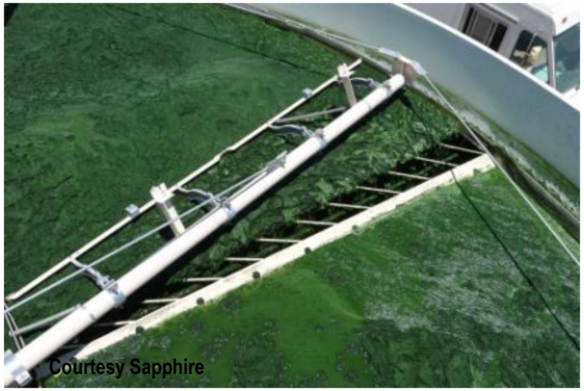
Algae Feedstocks

Activities include R&D on algal feedstocks and issues related to the sustainable production of algae-derived biofuels.

Benefits	Challenges
High productivity expands domestic biomass potential	Affordable and scalable algal biomass production
Adds value to unproductive or marginal lands	Feedstock production and crop protection
Ability to use waste and salt water	Energy-efficient harvesting and drying
Potential recycling of carbon dioxide	Extraction, conversion, and product purification
Production of a range of biofuel feedstocks suitable for diesel and aviation fuels	Siting and sustainability of resources


Courtesy University of Arizona


Courtesy Sapphire


Courtesy Sapphire

Microalgae Resource Assessment

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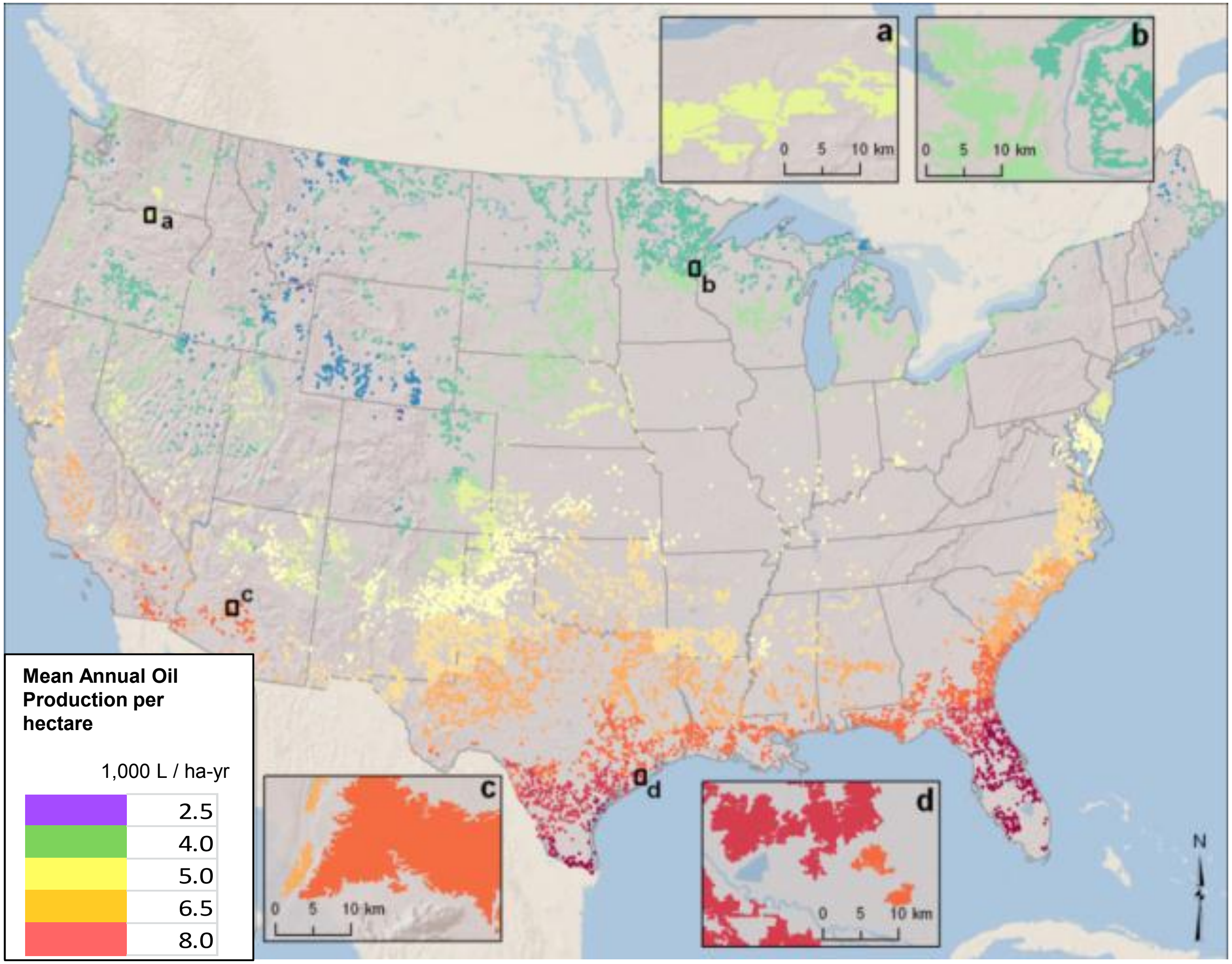

Wigmosta, M. S., A. M. Coleman, R. J. Skaggs, M. H. Huesemann, and L. J. Lane, 2011, National microalgae biofuel production potential and resource demand, Water Resour. Res., 47, W00H04

- A National resource assessment identified ~430,000 km^2 of suitable land for algae cultivation with potential for 58 BGY of algal oil production
- Optimizing to maximize productivity and minimize water use identifies 10,000 km^2, or about 3.7M acres, mainly around the Southwest and Gulf Coast
- These optimized sites would support production of 5 BGY

Biomass Program Algae Portfolio

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Research and Development

National Alliance for Advanced Biofuels and Bioproducts (NAABB)
- $50M in Recovery Act funds
- Led by the Donald Danforth Plant Sciences Center
- Director: Dr. Jose Olivares (Los Alamos National Laboratory)
- Biology, Cultivation, Harvest/Dewater, Extraction, Thermochemical Conversion, Sustainability, Co-products

Sustainable Algal Biofuels Consortium (SABC)
- Up to $6M in FY10 appropriated funds
- Led by Arizona State University
- Director: Dr. Gary Dirks
- Algae Production, Biochemical conversion, Fuel Testing

Consortium for Algal Biofuels Commercialization (CAB-Comm)
- Up to $9M in FY10 appropriated funds
- Led by UC San Diego
- Director: Dr. Steve Mayfield (UCSD)
- Nutrient Recycle, Crop Protection, Life-cycle Analysis

Cornell/Cellana Consortium
- Up to $9M in FY10 appropriated funds
- Led by Cornell University
- Director: Dr. Mark Huntley (Cornell)
- Cultivation (marine hybrid system), Systems Integration, Co-products

ASAP Selections – 2012
- Up to $21M in appropriated funds
- Establishes ATP3, a 5-year regional test bed partnership led by ASU with cites in HI, CA, AZ, OH, & GA
- Initiates 3 innovative nutrient and water recycle research projects

Demonstration and Deployment

Multi-Year Program Plan Goals

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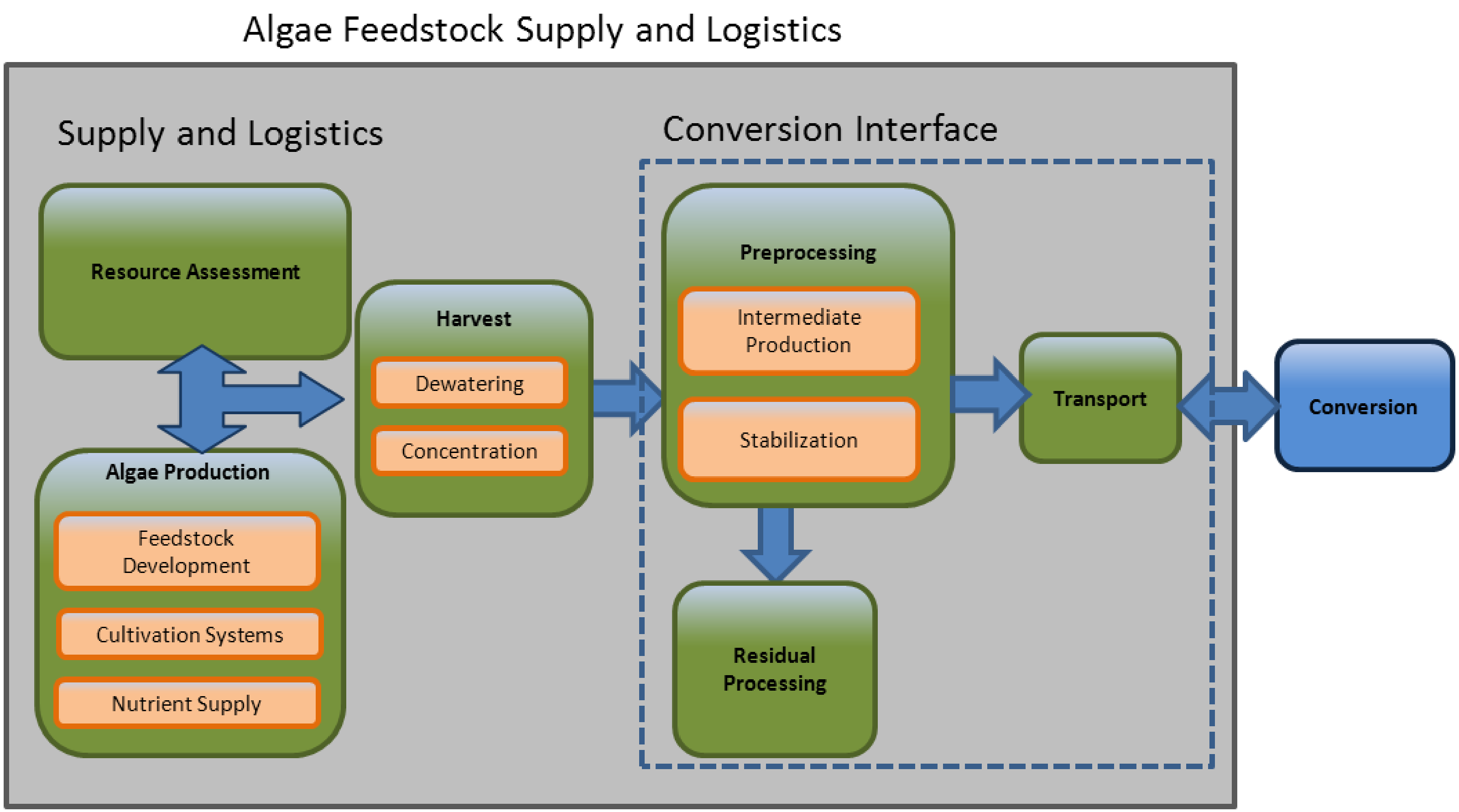
- The updated Biomass Multi-Year Program Plan (MYPP) including new algae feedstock section will be released in December
  - Strategic mission, performance goals, and cost projections for algae feedstocks supply and logistics systems based on an conservative, literature-based model of open-pond, neutral lipid extraction
  - Alternative designs evaluations continue
  - Additional pathways and complete design case expected once better integrated feedstock and conversion data and models available

- MYPP algae feedstock goal is high “biofuel intermediate” feedstock yield.
- Strategy focused increased productivity of large-scale algae cultivation and preprocessing while maximizing efficiency of water, land, nutrient, and power use to supply a stable biofuel intermediate for conversion to advanced biofuels
  - 10-year target is by 2022, demonstrate biofuel intermediate yield of >5,000 gallons per acre-year.
  - In the baseline TEA model, this feedstock yield corresponds to a projected modeled nth plant minimum selling price of $3.27 / gge of raw biofuel intermediate and $3.73 / gge of renewable diesel.

Algae Biofuel: Feedstock Supply and Logistics

This conceptual diagram outlines the main elements of a generalized algae feedstock supply system.



Pathways for Conversion

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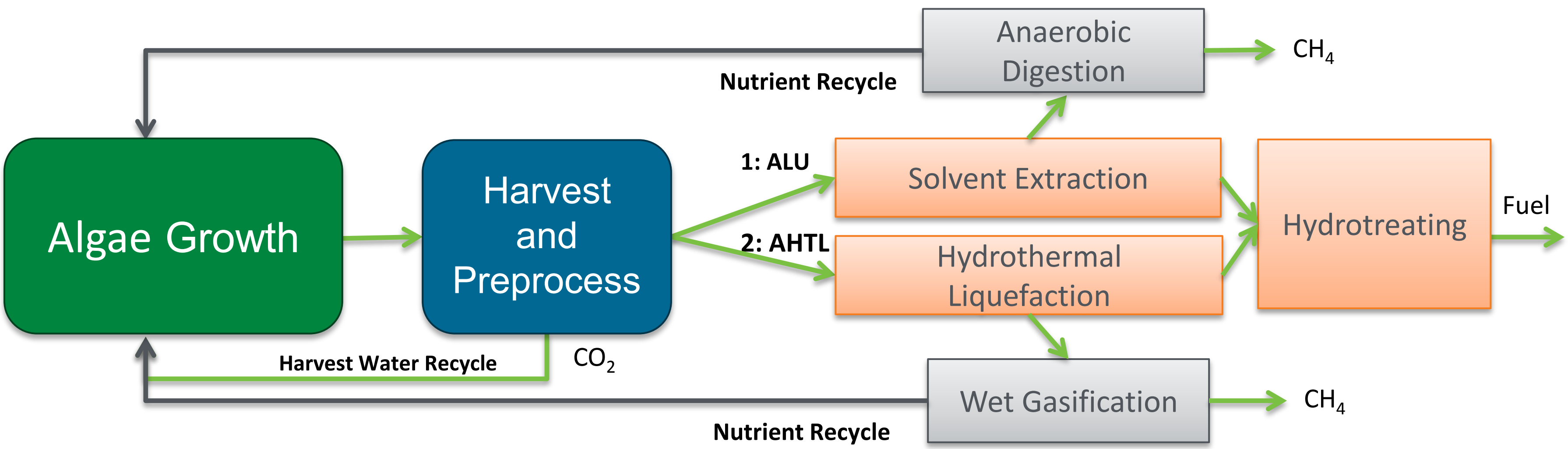
Two Baseline Pathways for Conversion of Algae to Fuels:

1. Algal Lipid Upgrading (ALU)
2. Algae Hydrothermal Liquefaction (AHTL)



Algae Model Harmonization Initiative

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- The Biomass Program uses a baseline algal production scenario with model-based quantitative metrics to inform strategic planning.

- Preliminary work on resource assessment (RA), techno-economic analysis (TEA), and life cycle analysis (LCA) integrated with external stakeholder input during Harmonization Workshop (Dec, 2011).

- ANL, PNL, NREL joint technical report “Renewable Diesel from Algal Lipids” in **June, 2012.**

- Subsequent workshops will be held to further the initiative and consider **whole algae hydrothermal liquefaction** and other innovative pathways.


Argonne NATIONAL LABORATORY

NREL NATIONAL RENEWABLE ENERGY LABORATORY

Pacific Northwest NATIONAL LABORATORY
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Renewable Diesel from Algal Lipids: An Integrated Baseline for Cost, Emissions, and Resource Potential from a Harmonized Model

Coordinating Authors: Ryan Davis,[3] Daniel Fishman,[2] Edward D. Frank,[1] Mark S. Wigmosta[4]

Contributing Authors: Andy Aden,[3] Andre M. Coleman,[4] Philip T. Pienkos,[3] Richard J. Skaggs,[4] Erik R. Venteris,[4] Michael Q. Wang[1]

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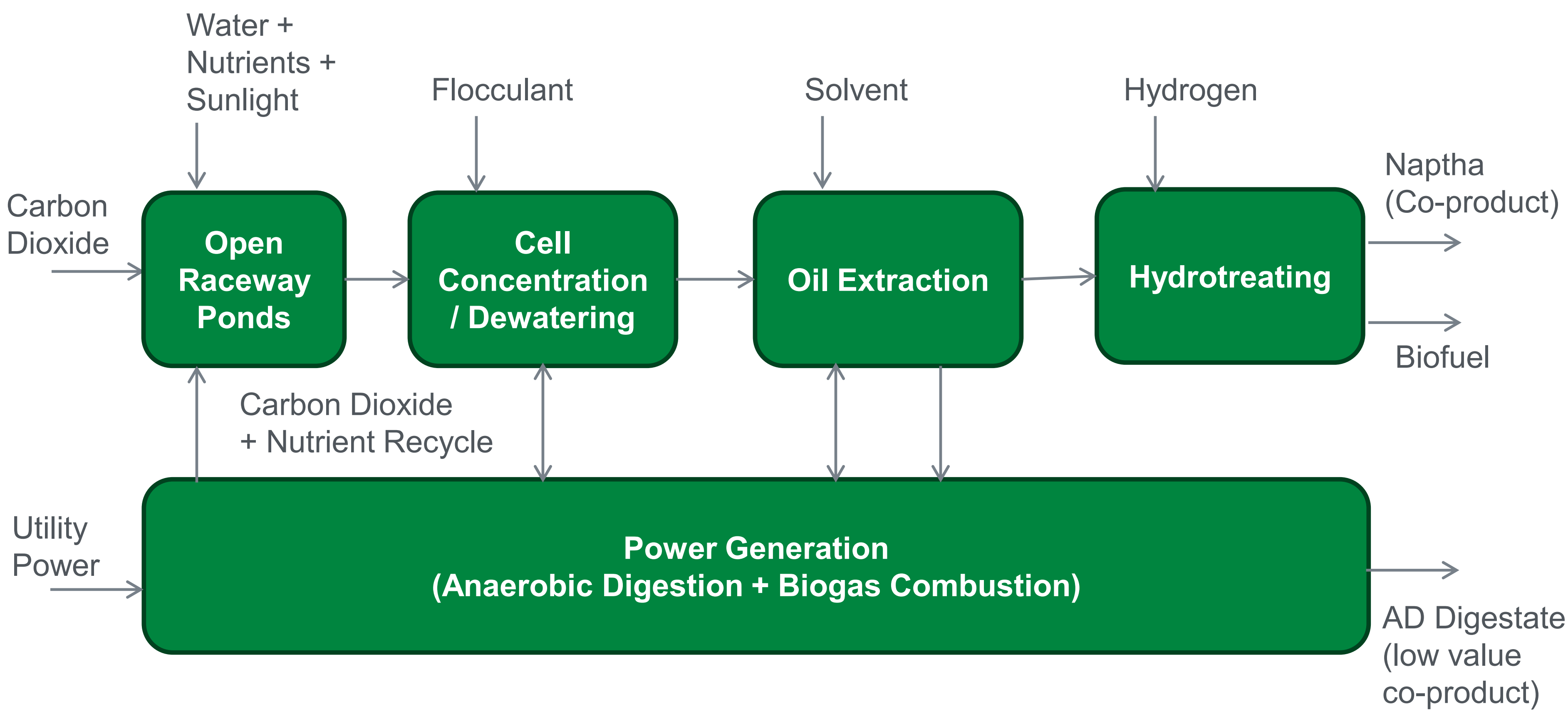
Pacific Northwest National Laboratory is operated by Battelle for the United States Department of Energy under contract DE-AC05-76RL01830.

Technical Report
ANL/ESD/12-4
NREL/TP-5100-55431
PNNL-21437
June 2012
Prepared for the U.S. Department of Energy Biomass Program

Integrated Baseline: ALU Pathway Process Flow Diagram



Baseline Performance and Sensitivity

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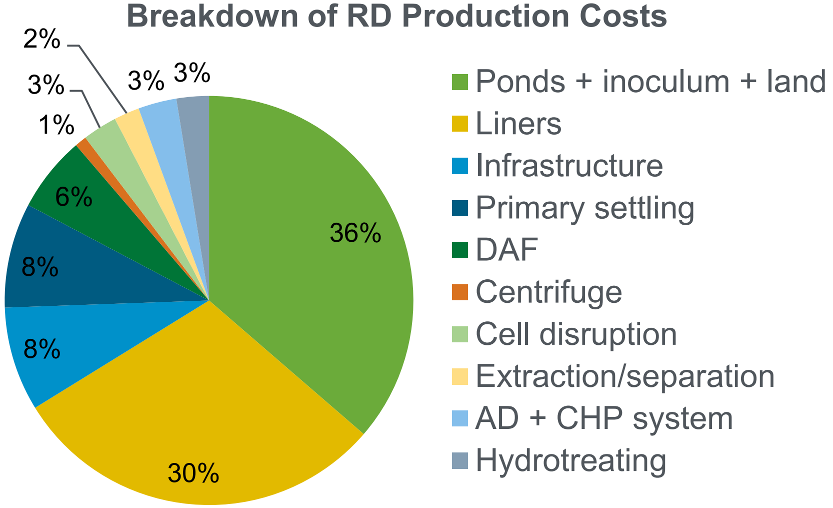
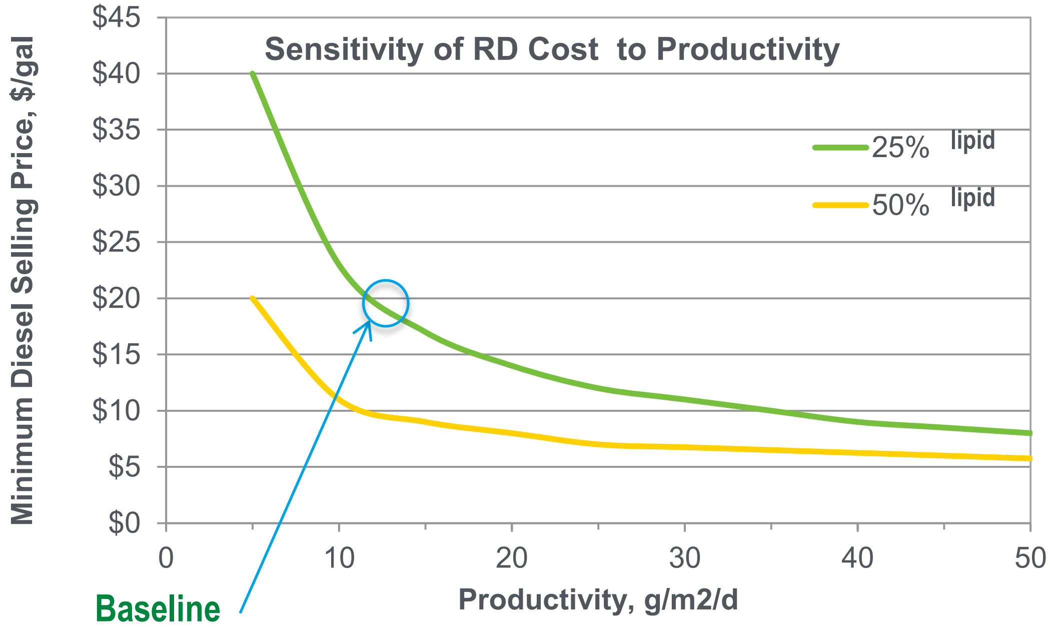
- Baseline assumption results:
  - Minimum Selling Price: ~$20/gallon
  - Emissions: 67,400 g cO2e/MMBTU RD
  - Water: 195 gal / gal RD

- The baseline performance is highly uncertain and small changes in productivity have large impacts

- Innovative work across the value chain is showing promise in reducing costs.

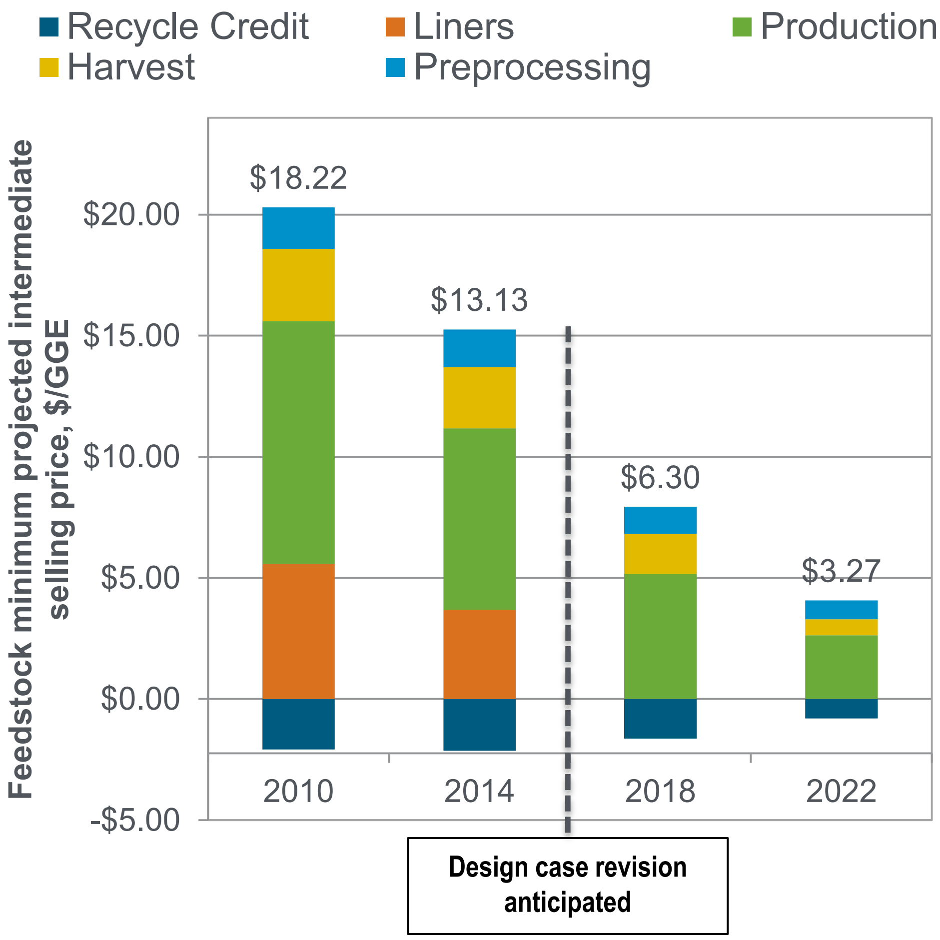
- Breakthroughs in productivity alone are not enough to achieve competitive MFSP





MYPP Cost Projections

Algae Production and Logistics Costs for Lipid Extraction (biofuel intermediate feedstock)



- Greatest opportunity to reduce costs is in the production systems.
  - through improved biomass yield and
  - reduced cultivation capital costs (by eliminating plastic pond liners).
- Significant cost improvements are also projected in feedstock harvest and preprocessing.
- Also shown explicitly is the value of the recycling credit achieved from processing the residual biomass via anaerobic digestion to produce on-site power and recover nitrogen and phosphorus.

AHTL Pathway: Potential downstream advantages?

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- Hydrothermal Liquefaction (HTL) of Whole Algae
  - HTL is both an extraction and a conversion process (50-70% of carbon in algae captured in oil)
  - Because the hydrocarbon structure of lipids is almost completely recovered, HTL can replace other lipid extractions such as solvent or alkali extraction of lipids
  - In addition, a portion of proteins and carbohydrates are converted to oil
  - The total oil yield is higher than other known extractions
  - Since HTL is a wet process using only water, no drying or solvent recovery is needed
- Catalytic Hydrodeoxygenation (HDO) of HTL bio-oil
  - Carbon retained during hydrotreating (70-90 wt%)
  - Oil phase is lower in oxygen content and likely easier to upgrade to hydrocarbons than fast pyrolysis derived bio-oil
- Catalytic Hydrothermal Gasification (CHG) produces methane
  - CHG is faster, smaller, and more complete than Anaerobic Digestion (AD)

AHTL Pathway: Process Flow Diagram

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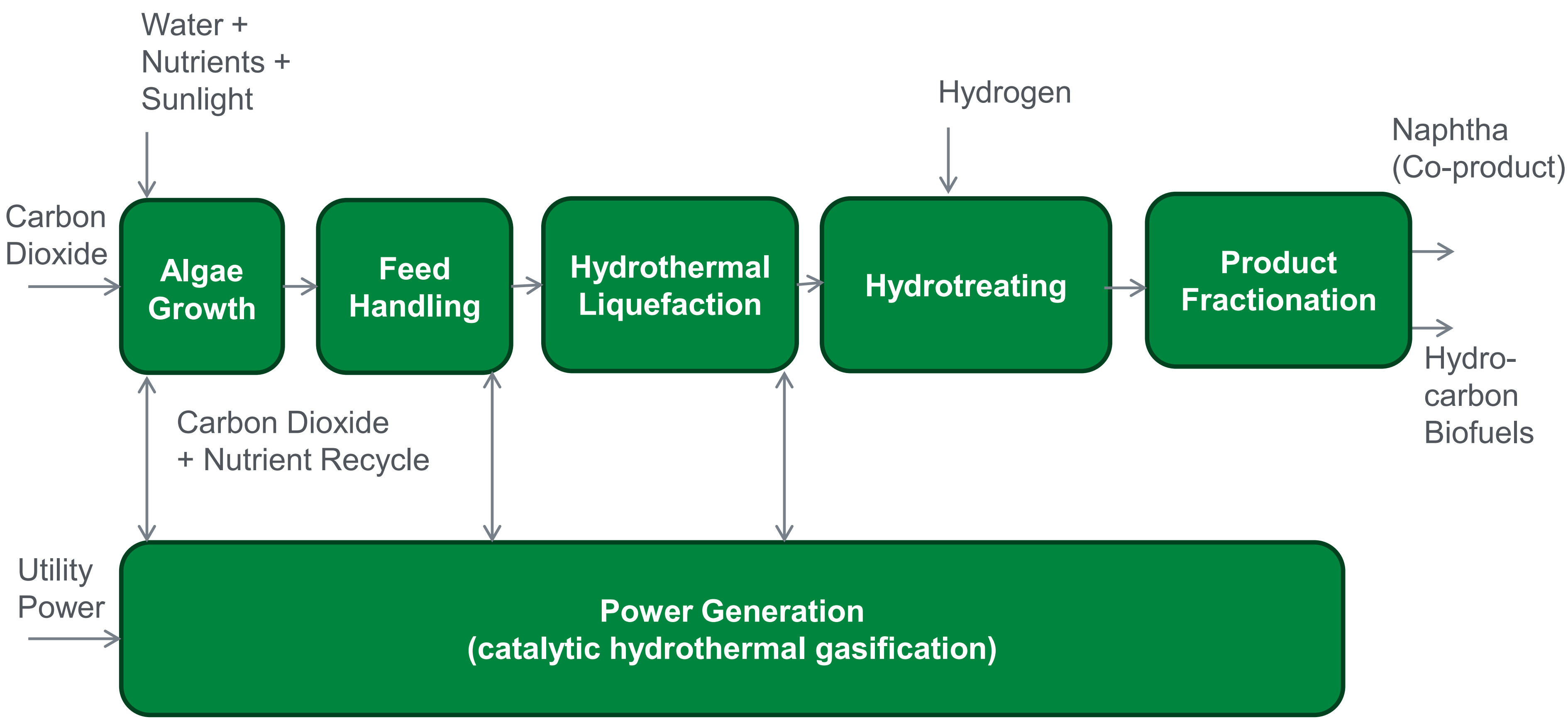
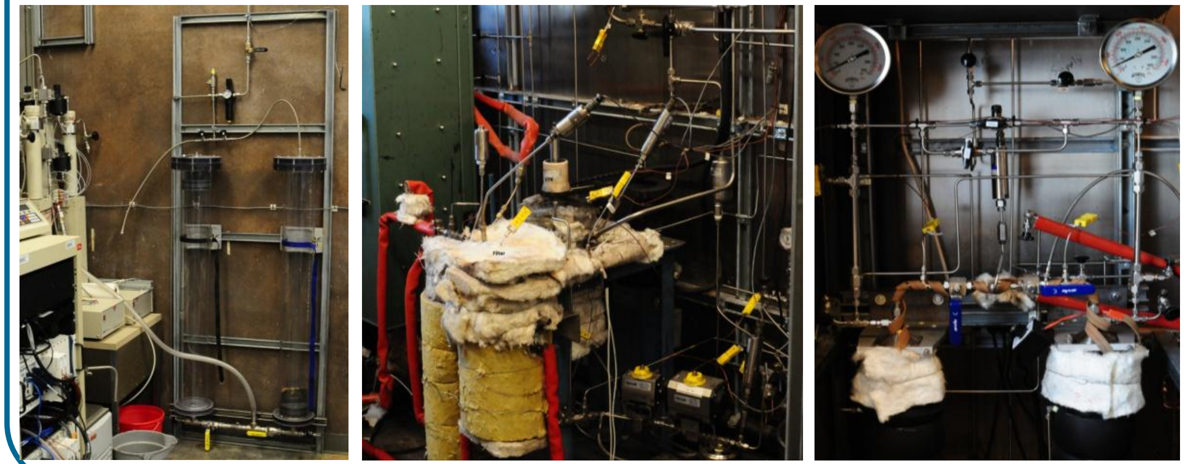


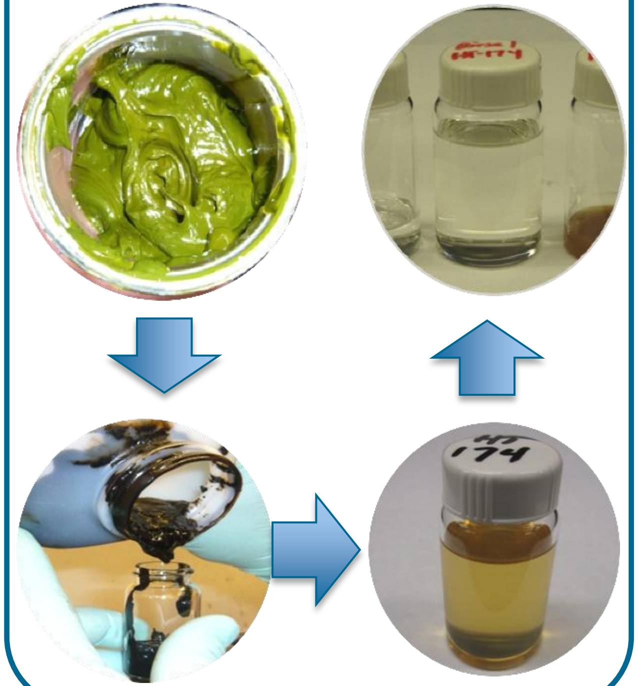
AHTL Pathway: Next Steps

HTL Bio-Oil Production—CSTR Configuration



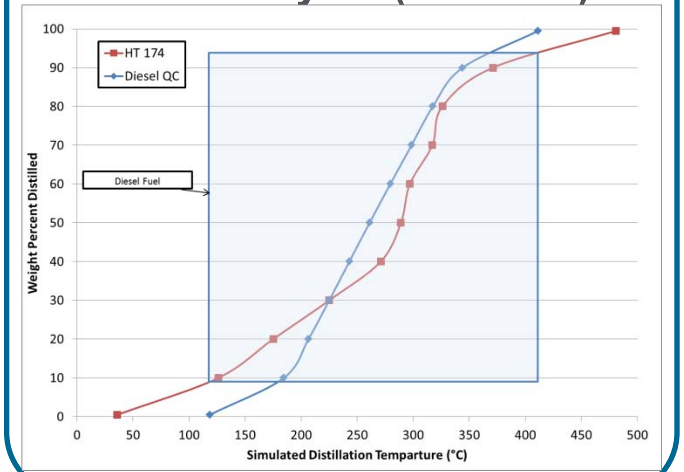
Algae to Fuels

- 57 - 70% of the carbon in algae captured in Oil
- Carbon retained during hydrotreating
- 80% in diesel range
- Aqueous carbon capture as biogas



Bio-Oil Upgrading

Fuel Analysis (Sim Dist)



AHTL Pathway: Design Basis Process Details

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Hydrothermal Liquefaction (HTL) of Whole Algae:

- **Feed handling**: Wet whole algal biomass (~ 20% solids) is pumped to the HTL reactor pressure of ~3000 psia.[1]
- **Hydrothermal Liquefaction (HTL):** Whole wet algae at ~ 20 wt% solids content is hydrothermally treated in subcritical water (2000-3000 psi and 300-350 °C) and 4 v/v/h liquid hourly space velocity (LHSV).[2]
- **Catalytic Hydrothermal Gasification (CHG):** Waste water from the HTL process (and upgrading if it is co-located) is sent to a catalytic hydrothermal gasification (CHG) process to convert all organics to CO_2 and CH_4. For CHG, the wastewater stream is pumped to ~3000 psia, and preheated to 350 °C , then fed to a fixed bed catalytic reactor.[3] Opportunity for nutrients recycle.
- **Hydrotreating:** The organic phase from HTL processing is catalytically hydrotreated to remove oxygen and most of the nitrogen. Bench scale experiments using HTL oil were run at 407 °C, ~2000 psia and an LHSV of 0.16 v/v/h to convert the oil to hydrocarbon, water and gas over a two-stage fixed bed reactor system.[2]

Questions?

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