Pathways for Algal Biofuels

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Daniel B. Fishman
Lead Technology Development Manager
Activities include R&D on algal feedstocks and issues related to the sustainable production of algae-derived biofuels.

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

Courtesy Sapphire

Courtesy Sapphire
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.

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
Multi-Year Program Plan Goals

- 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 a 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.
This conceptual diagram outlines the main elements of a generalized algae feedstock supply system.
Two Baseline Pathways for Conversion of Algae to Fuels:
1. Algal Lipid Upgrading (ALU)
2. Algae Hydrothermal Liquefaction (AHTL)
• 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.
Integrated Baseline: ALU Pathway Process Flow Diagram

Water + Nutrients + Sunlight → Flocculant → Solvent → Hydrogen

Open Raceway Ponds → Cell Concentration / Dewatering → Oil Extraction

Carbon Dioxide → Carbon Dioxide + Nutrient Recycle

Utility Power

Hydrotreating

AD Digestate (low value co-product)

Biofuel

Power Generation (Anaerobic Digestion + Biogas Combustion)
Baseline Performance and Sensitivity

- 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
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?

• 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

Water + Nutrients + Sunlight → Algae Growth → Feed Handling → Hydrothermal Liquefaction → Hydrotreating → Product Fractionation

Carbon Dioxide + Nutrient Recycle → Carbon Dioxide

Hydrogen

Naphtha (Co-product)

Utility Power → Power Generation (catalytic hydrothermal gasification) → Hydrocarbon Biofuels
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)

FOR DOE OBP PURPOSES ONLY
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 CO₂ and CH₄. 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?

Watch our news feed at www.eere.energy.gov/biomass for information of RFIs, funding, and conferences