The Promises and Challenges of Algal-Derived Biofuels

IEA Bioenergy Algal Biofuels Workshop
Liege, Belgium
October 1, 2009

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Outline

Potential of Algal Biofuels
DOE’s former Aquatic Species Program: Lessons learned
What’s changed since 1996?
Challenges of Algal Biofuels: Myth vs reality
Algal Biofuels Workshops and Reports
Algal Biology Considerations
IEA Task 39 Algal Biofuels Report: International Efforts
Conclusions
Biofuel Challenges: Energy Density

Cellulosic ethanol addresses the gasoline market
- U.S. gasoline usage: 140 billion gallons/year

Does not address need for higher-energy density fuels
- U.S. diesel usage: 44 on-road/20 off-road billion gallons/year
- U.S. jet fuel usage: 25 billion gallons/year

<table>
<thead>
<tr>
<th>Energy Densities</th>
</tr>
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<tbody>
<tr>
<td>Ethanol</td>
</tr>
<tr>
<td>76,330 Btu/gal</td>
</tr>
</tbody>
</table>

Dilemma: Biodiesel from current oilseed crops cannot come close to meeting U.S. diesel demand (44 billion gal/year)
- Soy oil (2.75 B gal; 2007); replaces ~4% of U.S. demand
- Vegetable oils must compete with food market
- 2.5B gallon capacity, only 700M gallons produced in 2008

Alternative sources of oils are needed!
Algae: Numerous Bioenergy Routes

Defining a Biofuels Portfolio From Microalgae

Microalgae

- Hydrogen
- Lipids or Hydrocarbons

Macroalgae

- Carbohydrates
- Biomass

Intermediate

- Syngas
- Methane

Fuel

- Hydrogen
- Alkanes or “Green Diesel”
- Biodiesel
- Alcohols (Ethanol)
- FT Liquids
- Methane

Microalgae: a source of energy
- Wastewater bioreactors
- Information from cell culture aroma
- Exploring relationships between biological objects

Biofuels Portfolio

- FT Liquids
- Methane
Why Fuels from Algal Oil?

- High-lipid content (up to 50%); rapid growth; more lipids than terrestrial plants --10x - 100x
- Can use non-arable land; saline/brackish water
- No competition with food, feed or fiber
- Utilize large waste CO₂ resources (i.e., flue gas)
- Potential to displace significant U.S. petroleum fuel usage – requires low-cost infrastructure

Images courtesy: Lee Elliott, CSM

Fluorescence micrograph showing stained algal oil droplets (green)
Comparing Potential Oil Yields

<table>
<thead>
<tr>
<th>Crop</th>
<th>Oil Yield Gallons/acre</th>
</tr>
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<tbody>
<tr>
<td>Corn</td>
<td>18</td>
</tr>
<tr>
<td>Cotton</td>
<td>35</td>
</tr>
<tr>
<td>Soybean</td>
<td>48</td>
</tr>
<tr>
<td>Mustard seed</td>
<td>61</td>
</tr>
<tr>
<td>Sunflower</td>
<td>102</td>
</tr>
<tr>
<td>Rapeseed</td>
<td>127</td>
</tr>
<tr>
<td>Jatropha</td>
<td>202</td>
</tr>
<tr>
<td>Oil palm</td>
<td>635</td>
</tr>
<tr>
<td>Algae (20g/m²/day-15%)</td>
<td>1267</td>
</tr>
</tbody>
</table>

Image courtesy: Q. Hu, ASU
# Algae Compared to Ethanol Crops

<table>
<thead>
<tr>
<th>Biomass</th>
<th>Productivity</th>
<th>Energy (GJ/acre)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>90 MJ/gallon ethanol</td>
</tr>
<tr>
<td>Sugar Cane</td>
<td>35 tons/acre</td>
<td>62 GJ/acre (sugar to ethanol only)</td>
</tr>
<tr>
<td></td>
<td>700 gal/acre - sugar</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1440 gal/acre - bagasse</td>
<td></td>
</tr>
<tr>
<td>Corn</td>
<td>8 tons/acre</td>
<td>36 GJ/acre (starch to ethanol only)</td>
</tr>
<tr>
<td></td>
<td>405 gal/acre - grain</td>
<td></td>
</tr>
<tr>
<td></td>
<td>420 gal/acre – corn stover</td>
<td></td>
</tr>
<tr>
<td>Algae</td>
<td>32 tons/acre (20 gm/m²/day @15%)</td>
<td>162 GJ/acre (oil only)</td>
</tr>
<tr>
<td></td>
<td>1267 gallons/acre</td>
<td></td>
</tr>
<tr>
<td></td>
<td>49 tons/acre (30 gm/m²/day @15%)</td>
<td>243 GJ/acre (oil only)</td>
</tr>
<tr>
<td></td>
<td>1899 gallons/acre</td>
<td></td>
</tr>
<tr>
<td></td>
<td>49 tons/acre (30 gm/m²/day @ 30%)</td>
<td>486 GJ/acre (oil only)</td>
</tr>
<tr>
<td></td>
<td>3799 gallons/acre</td>
<td></td>
</tr>
</tbody>
</table>
# Resource Requirements

<table>
<thead>
<tr>
<th></th>
<th>Soybean</th>
<th>Algae*</th>
</tr>
</thead>
<tbody>
<tr>
<td>gal/year</td>
<td>3 billion</td>
<td>3 billion</td>
</tr>
<tr>
<td>gal/acre</td>
<td>48</td>
<td>1267</td>
</tr>
<tr>
<td>Total acres</td>
<td>62.5 million**</td>
<td>2.4 million</td>
</tr>
<tr>
<td>Water usage</td>
<td>ND</td>
<td>6 trillion gal/yr***</td>
</tr>
<tr>
<td>CO₂ fixed</td>
<td>ND</td>
<td>79 million tons/yr</td>
</tr>
</tbody>
</table>

* algae (open ponds) productivity of 10 g/m²/day with 30% TAG.
** Total land area: 73 million acres
*** 50 trillion gallons used annually for irrigation of crops in the US

- World emits ~ 32 Gt CO₂; ~17 Gt is absorbed; 15 Gt remains in atmosphere
- 1 Gt CO₂ can produce ~40 B gallons algal oil
- Average coal power plant (600-700 MW) produces 4M tons CO₂ per year
DOE’s Aquatic Species Program

A Look Back at the U.S. Department of Energy’s Aquatic Species Program: Biodiesel from Algae

Outdoor Culture Studies and Systems Analysis

Algae Production in Wastewater Treatment

Production of Microalgae for Fuels

Systems Analysis and Resource Assessment

1000 sq.m. Pond Study (NM)

<100 sq.m. Pond Studies (CA, HI)

Transient expression of foreign gene in algae using protoplasts

1st successful genetic transformation of diatom

By 1987, over 3,000 strains of algae had been collected.

Isolation and characterization of ACCase enzyme

Genetic Engineering of Algae

Biochemistry, Physiology of Lipid Production

Link between Si-deficiency and ACCase

N-deficiency lipid trigger

Si-deficiency lipid trigger

Nile Red lipid screening

Collection, Screening, Characterization

Cambean, NM, CO, UT, FL, HI, NE, AL

Arizona, CA, NV, NM, TX, UT

CO, AL, MI

UT, WA, CO, CA, NV

Close-Out Report

Production of Microalgae for Fuels

National Renewable Energy Laboratory

Innovation for Our Energy Future
Microalgae Collection and Screening: Lessons Learned

– Many microalgae can accumulate neutral lipids
– Diatoms and green algae most promising
– No perfect strain for all climates, water types
– Choosing the right starting strain is critical
Cellular Lipid Content of Algae

Physiology, Biochemistry, and Genetic Engineering: Lessons Learned

– Lipid induction with nutrient stress doesn’t help productivity
– Key enzymes increase upon induction, but no obvious “lipid trigger”
– We have only begun to scratch the surface
  • Understand lipid pathways & regulation; devise genetic strategies
Process Engineering: **Lessons Learned**

- Flocculation most promising route for harvesting & dewatering?
- Solvent extraction of oil is feasible; but is it economical?
- Development of harvesting and extraction methods will need a better understanding of cell wall ultra-structure and composition.

*Photos courtesy: Q. Hu, ASU*
ASP Close-Out Report: Future Directions

- Less emphasis on field demos; more on basic/applied biology
- Take advantage of plant biotechnology
- Start with what works in the field
- Maximize photosynthetic efficiency
- Set realistic expectations for the technology
- Look for near term technology deployment such as waste water treatment

http://www.nrel.gov/docs/legosti/fy98/24190.pdf
What’s Changed Since 1996?

• Record oil prices; increasing demand
• CO$_2$ capture and GHG reduction
• Industrial interest (>150 algal companies)
• Interest by oil industry, venture capital, end users, utilities and governments
• Explosion in biotechnology
Microalgal fuels have a huge potential….

Scenarios for producing substantial amount of diesel from microalgae are not unrealistic.
… but significant challenges still exist

**Algal Cultivation**
- Photobioreactor design
- Capital and operating costs
- Temperature control
- Saline water chemistries
- Makeup water (evaporation)
- CO₂ availability and transport
- Nutrient requirements
- Starting species
- Growth rate
- Oil content & FA profile
- Robustness
- Resistance to invasion
- Biofouling in closed systems
- Nutrient induction requirement
- Environmental impact, containment

**Oil (Lipid) Recovery**
- Harvesting
  - De-watering methods
  - Lipid extraction
  - Purification
- Costs, energy input
- Environmental issues
- Value from residual biomass

**Fuel Production**
- Process optimization
  - Fatty acid profiles
  - Costs and LCA
- Fuel characteristics
  - Energy density
  - Carbon numbers
  - Cloud point
  - Stability
  - Consistency
  - Additives required
  - Engine testing
  - ASTM standard

**Sustainable Land, Water and Nutrient Use**
Myth vs Reality

Wide range of projections...

What is the ultimate upper limit?

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Algae Oil Projections

- (1) Schenk, 2008
- (2) Chisti, 2007 (30% oil)
- (3) NREL ASP, Sheehan et al., 1998
- (4) Schenk, 2008
- (5) Chisti, 2007 (70% oil)
- (6) Report on CNN, Apr 4, 2008
Need to Obey Laws of Thermodynamics

1\textsuperscript{st} law: conservation of energy
\[ E_{in} - E_{out} = E_{stored} \]

2\textsuperscript{nd} law: 100\% efficiency is not possible
\[ E_{in} > E_{stored} \]
Inefficiencies galore.....

- Non-PAR solar energy
- Light transmission loss
- Reduced photon absorption
- Inherent photosynthetic loss
- Cellular energy use
- Non-oil biomass
- Energy STORED as oil

Energy IN as sunlight
Industry needs to well grounded….  

**Theoretical maximum oil production @ 50% oil; at the equator:**  
38,000 gal·acre⁻¹·yr⁻¹

**Best case range @ 50% oil:**  
4,350 – 5,700 gal·acre⁻¹·yr⁻¹

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**Algae Oil Projections**


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(1) Schenk, 2008  
(2) Chisti, 2007  
(3) NREL ASP, Sheehan et al., 1998  
(4) Schenk, 2008  
(5) Chisti, 2007  
(6) Report on CNN, Apr 4, 2008
Recent Algal Biofuels Reports and Roadmapping Activities
2007 Energy Independence and Security Act (EISA)

- Increase availability of renewable energy that decreases GHG emissions
- Increases Renewable Fuel Standard (RFS) to 36 B gallons by 2022.
- (Section 228) Requires Energy Secretary to present to Congress a report on the feasibility of microalgae as a feedstock for biofuels production.
Congressional Algae Report

Microalgae Feedstocks for Biofuels Production

Report to Congress

Microalgae Feedstocks for Biofuels Production
(EISA 2007 – Section 228)

March 14, 2008

U.S. Department of Energy

Report Outline

• Executive Summary
• Introduction
• Historical Review of Technical Progress
• Microalgae Oil Production: Biology and Physiology
• Microalgae Oil to Biofuels
• Current Activities/Funding Support for Algae Biofuels
• Resource and Technoeconomic Assessment
• Conclusions and Recommendations
National Renewable Energy Laboratory and
Air Force Office of Scientific Research
Joint Workshop on
Algal Oil for Jet Fuel Production
February 19-21, 2008
Arlington, VA

http://www.nrel.gov/biomass/algal_oil_workshop.html
Algal Strain Research Recommendations

- Publically available strain database and resource center
- Isolation of novel strains vs culture collection strains
- Model organism(s): multiple model organisms
- Ramp up sequencing of algal genome
- Establish consortium of researchers to annotate genomes and perform extensive comparative analysis
- Lipid metabolism/carbon partitioning pathways in algae are largely uncharacterized
- Systems biology approaches to aid in identifying metabolic fluxes and regulatory networks
- Development of genetic tool kits
Venue: Univ. of Maryland Dec. 9-10, 2008

Participants: ~200 scientists, engineers and other experts in various disciplines

Goal: Define activities needed to resolve barriers associated with commercial scale algal biofuel production

Workshop: plenary presentations and breakout sessions covering technical, industrial, resource, and regulatory aspects of algal biofuel production

Information: http://www.orau.gov/algae2008/

Progress: First draft of Roadmap complete; comments solicited through RFI process; editing in progress; completed roadmap scheduled to be released Fall 2009

http://www1.eere.energy.gov/biomass/pdfs/algalbiofuels.pdf
Fundamental and applied research needed to resolve uncertainties associated with commercial-scale algal biofuel production:

Roadmap Chapters
- Algal Biology
- Cultivation
- Harvest/dewatering
- Extraction/fractionation
- Conversion to fuels
- Co–products
- Distribution and Utilization
- Resources and Siting
- Stds, Regulation & Policy
- Systems and TE analysis
- Public-Private Partnerships
Feedstock: Algal Biology

- Strain isolation and screening
- Cell biology and physiology
- Genetic toolbox
- Systems biology
Technoeconomic Modeling

- Determine current state of technology
- Identify critical path elements that offer best opportunities for cost reduction
- Identify research areas most in need of support
- Measure progress towards goals
- Provide sanity check for independent modeling efforts
- Identify external factors that will impact cost
- Provide plan for entry of algal biofuels into renewable fuel portfolio
IEA Bioenergy Task 39
Algal Biofuels Technology Report
**Executive Summary**

1. Introduction
   1.1 Background
   1.2 The World’s Energy Challenges
   1.3 Algae: Definitions, Basic Biological Concepts
   1.4 Non-fuel Applications and geographic distribution of algal cultivation
   1.5 The Algae-to-Biofuels Opportunity
   1.6 Benefits of Algal Oil Production
   1.7 Comparison to Terrestrial Crops

2. Historical Review of Technical Progress
   2.1 Early work
   2.2 DOE’s Aquatic Species Program
   2.3 Other International Efforts
   2.4 Research from 1996 to present
   2.5 Current activities and Funding Support for Algal Biofuels Research

3. Microalgae Oil Production
   3.1 Algal Biology and Physiology
      3.1.1 Introduction
      3.1.2 Technology Status
         3.1.2.1 Photosynthesis and CO2 fixation
         3.1.2.2 Lipid biosynthetic pathways
         3.1.2.3 Lipid analysis
         3.1.2.4 Genomics
         3.1.2.5 Genetic manipulation
         3.1.2.6 Culture Collections
      3.1.3 Technology Challenges
   3.2 Cultivation
      3.2.2 Current Industrial Microalgae Cultivation Technologies
      3.2.3 Algal Photobioreactor Designs
      3.2.4 Technology Challenges
   3.3 Harvesting and dewatering
      3.3.1 Introduction
      3.3.2 Technology Status: Processing technologies
      3.3.3 Technology Challenges
   3.4 Extraction and Fractionation of Microalgae
      3.4.1 Introduction
      3.4.2 Technology Status
      3.4.3 Technology Challenges
   3.5 Conversion of microalgal oils to fuels
      3.5.1 Introduction
      3.5.2 Technology Status

4. Co-products
   4.1 Introduction
   4.2 Commercial products
   4.3 Potential Co-products from an Algal Biofuels Production Facility

5. Resources and siting
   5.1 Introduction
   5.2 Resource assessment
   5.3 Siting

6. Systems and Technoeconomic Analysis
   6.1 Introduction
   6.2 Systems analysis
   6.3 Techno-economic analysis
International Algal Biofuels Efforts

- **Australia**, SARDI and CSIRO in S. Australia and M. Borowitzka in W. Australia
- **Belgium**, Sbae Industries (Diaforce)
- **Brazil**, Petrobras starting project in Northeast of Brazil
- **Canada**, National Research Council and Natural Resources Canada
- **China**, Oil companies; Wuhan and Qingdao
- **Germany**, RWE and E.ON projects
- **India**, Resource assessment in progress
- **Israel**, Seambiotic
- **Italy**, Eni project at Gela refinery; building about half an hectare of ponds
- **The Netherlands**, University and industrial efforts
- **New Zealand**, ChristChurch, NIWA and Solray; AquaFlow
- **UK**, The Carbon Trust ABC (algae biofuels challenge) program
Conclusions

• After 13 yrs, DOE ramping up support for algal biofuel RD&D
• International efforts are also drawing considerable attention
• Infrastructure does not exist for an algal biofuels industry
• Workshops and roadmaps provide foundation for support
• Technoeconomic modeling and Life-Cycle Assessments provides insight into critical path to commercialization
  – Biological productivity key to reduce costs regardless of process
  – Public economic models indicate overall technological uncertainties
  – Sustainability, sustainability, sustainability,….
• RD&D support needed for all elements of value chain
  – Basic science to process engineering
  – Bench scale to demo facility
  – Fully integrated to ensure commercial relevance
Conclusions (continued)

- **Risk**
  - Relevant policies and regulations not crafted with algal biofuels in mind
  - Regulatory landscape confusing and contradictory

- **Uncertainty**
  - Standards exist for algal products but not for production processes
  - Financial incentives to level playing field and advance industry as a whole
  - Policies promoting algal biofuels can also incentivize
    - Food and feed production
    - Water remediation
    - Job creation
    - Education
    - International competitiveness

- **IEA Bioenergy Task 39 Algal Biofuels Report**
  - Opportunity to bring together the international algal biofuels efforts
Acknowledgments

Mike Pacheco  Andy Aden  Qiang Hu (ASU)
Eric Jarvis  Maria Ghirardi  Milt Sommerfeld (ASU)
Phil Pienkos  Mike Seibert  Bryan Willson (CSU/Solix)
Yat-Chen Chou  Jianping Yu  Kristina Weyer (Solix)
Eric Knoshaug  Pin-Ching Maness  Dan Bush (CSU)
David Crocker  Ed Wolfrum  Walt Kozumbo (AFOSR)
Ryan Sestric  Lieve Laurens  Ami Ben-Amotz (Seambiotic)
Rich Bain  Jim Duffield  Grant Heffelfinger (Sandia)
Matt Ringer  Anelia Milbrandt  Ron Pate (Sandia)
Nick Nagle  Bob Wallace  Matt Posewitz (CSM)
Mike Cleary  Helena Chum  Lee Elliott (CSM)

Financial Support
• NREL
• Chevron
• AFOSR
• C2B2
• DOE-EERE
• IEA Bioenergy Task 39

Algal biofuels research at NREL: http://www.nrel.gov/biomass/proj_microalgae.html