National Renewable Energy Laboratory
Innovation for Our Energy Future

Recent and Current Research & Roadmapping Activities: Overview

DOE Algal Biofuels Workshop

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NREL

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NREL/PR-510-45609

Outline

- Overview of algal biofuels activity (1996 – present)
- Status of algal biofuels research funding
- Recent algal biofuels roadmapping activities

Biomass Program

Algal Biofuels

Biofuels made from microalgae hold the potential to solve many of the sustainability challenges facing other biofuels today.

Growing America's Energy Future

Algal biofuels are generating considerable interest around the world. They may represent a sustainable pathway for helping to meet the U.S. biofuel production targets set by the Energy Independence and Security Act of 2007.

Microalgae are single-cell, photosynthetic organisms known for their rapid growth and high energy content. They are capable of doubling their mass several times per day, and more than half of that mass consists of lipids or triacylglycerides— the same material found in vegetable oils. These bio-oils can be used to produce such advanced biofuels as biodiesel, green diesel, green gasoline, and green jet fuel.

Renewed Interest and Funding

Higher oil prices and increased interest in energy security have stimulated new public and private investment in algal biofuels research. The Biomass Program is reviving its Aquatic Species Program at the National Renewable Energy Laboratory (NREL) to build on past successes and drive down the cost of large-scale algal biofuel production. Private investors as well as programs within the Defense Advanced Research Projects Agency (DARPA) and Air Force Office of Scientific Research (AFOSR) are also sponsoring research at NREL, Sandia, and other laboratories. Substantial research and development challenges remain.

Benefits of Algal Biofuels

Impressive Productivity:
Microalgae, as distinct from seaweed or macroalgae, can potentially produce 100 times more oil per acre than soybeans—or any other terrestrial oil-producing crop.

Non-Competitive with Agriculture:
Algae can be cultivated in large open ponds or in closed photobioreactors located on non-arable land in a variety of climates (including deserts).

Undemanding of Fresh Water:
Many species of algae thrive in seawater, water from saline aquifers, or even wastewater from treatment plants.

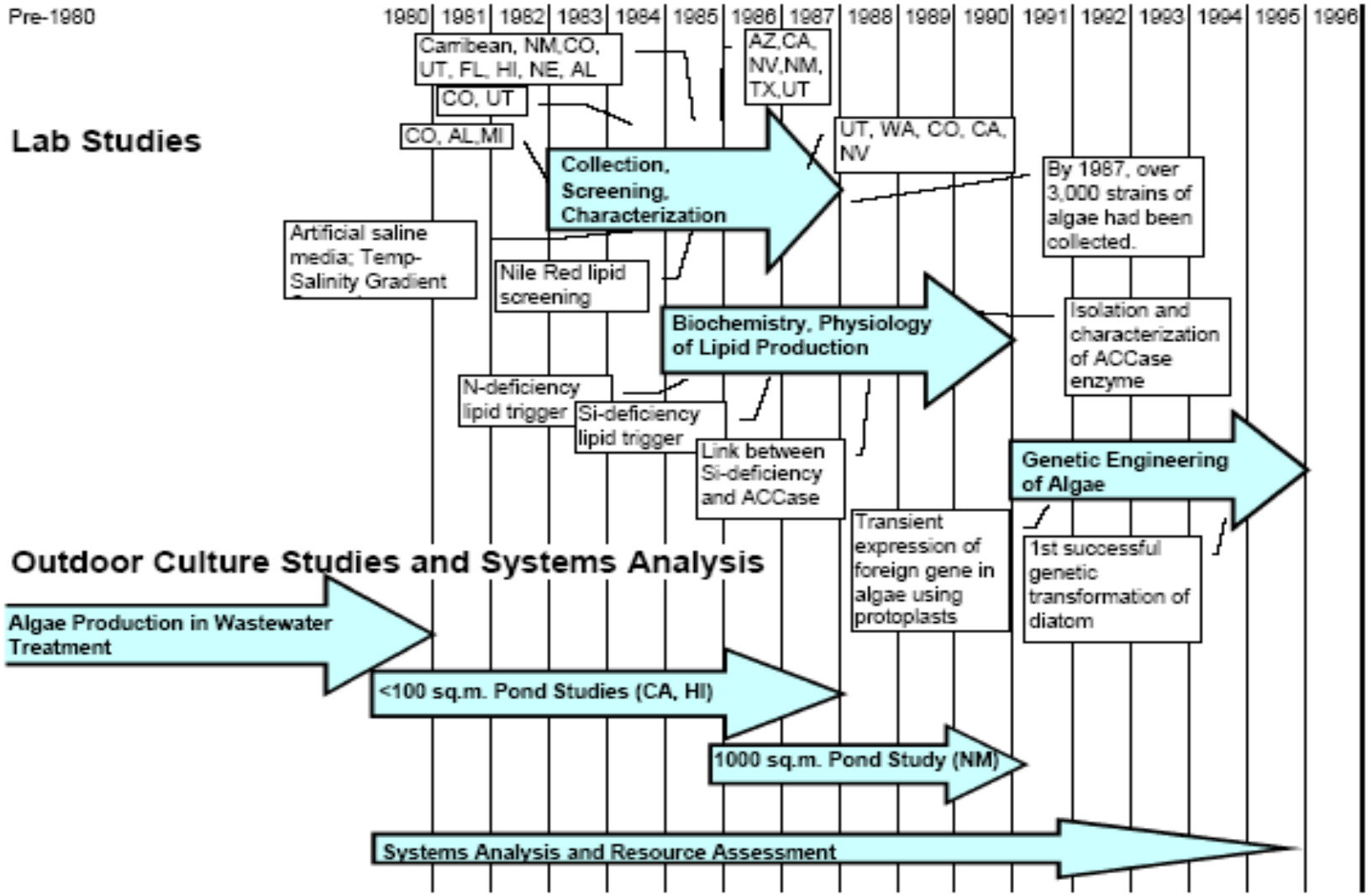
Mitigation of CO2:
During photosynthesis, algae use solar energy to fix carbon dioxide (CO_2) into biomass, so the water used to cultivate algae must be enriched with CO_2. This requirement offers an opportunity to productively use the CO_2 from power plants, biofuel facilities, or other sources.

Broad Product Portfolio:
The lipids produced by algae can be used to produce a range of biofuels, and the remaining biomass residue has a variety of useful applications:

- combust to generate heat
- use in anaerobic digesters to produce methane
- use as a fermentation feedstock in the production of ethanol
- use in value-added byproducts, such as animal feed

http://www1.eere.energy.gov/biomass/pdfs/algalbiofuels.pdf

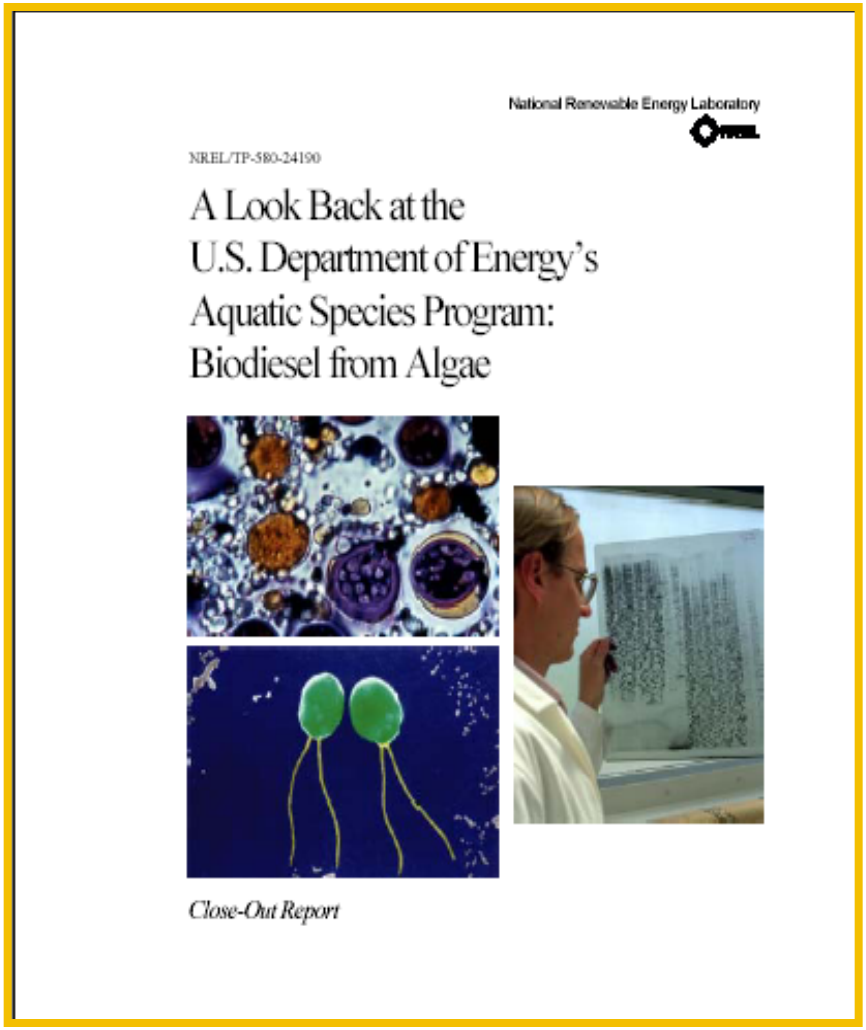
DOE's Aquatic Species Program



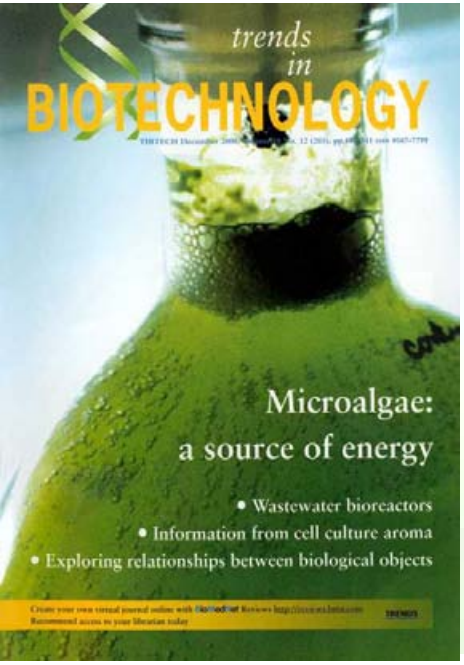
Algal Biofuels Technology Roadmap Workshop

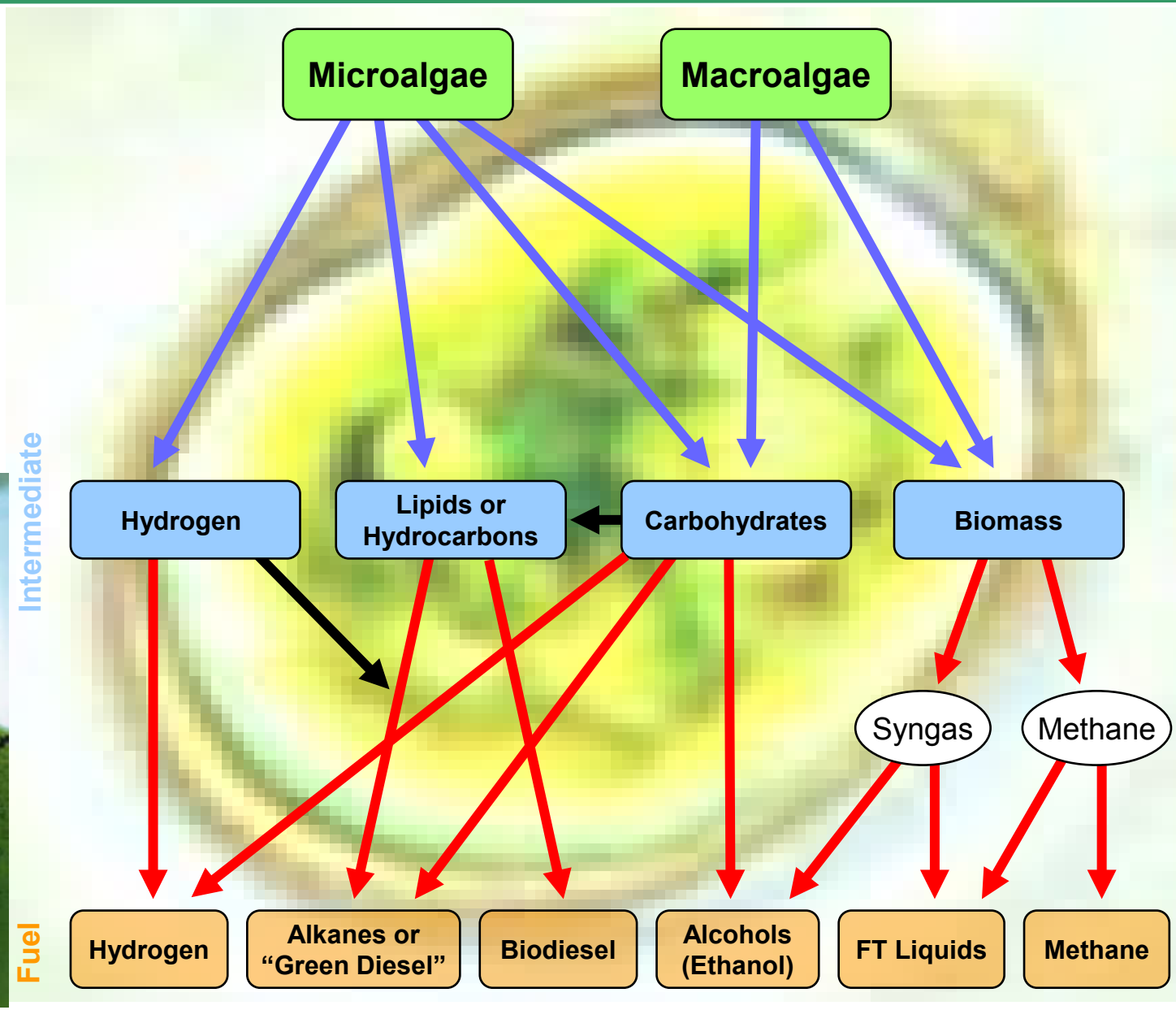
Sponsored by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE), Office of the Biomass Program

- ✓ Algal Biology
- ✓ Cultivation
- Harvesting/Dewatering/Extraction
- Conversion to Fuels
- Systems Integration
- CO_2 sourcing, siting, resources
- Regulatory/policy

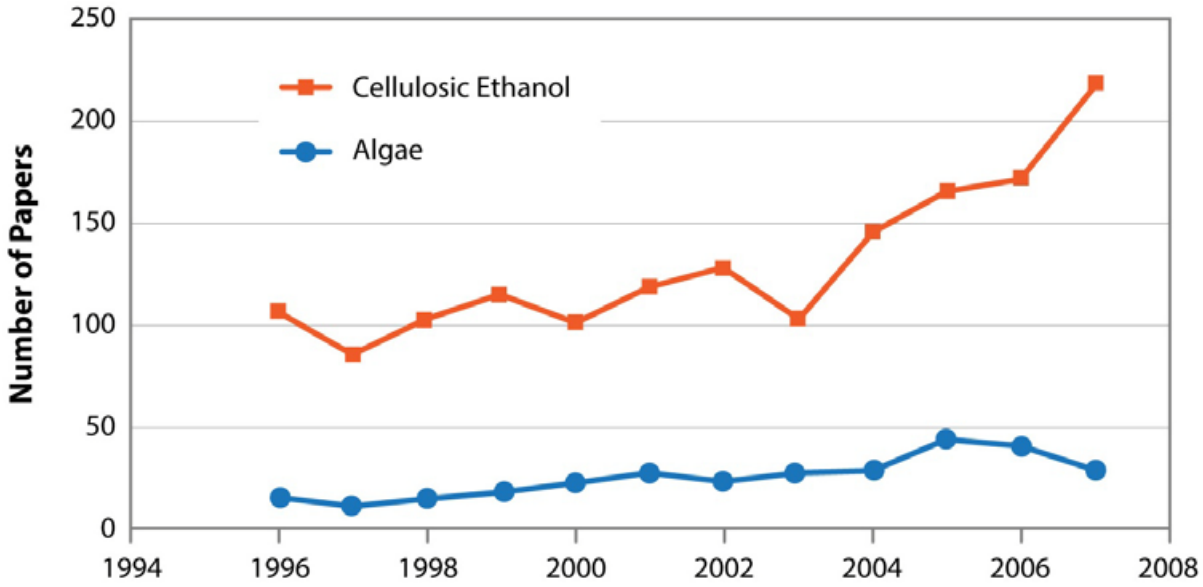


Algae: Numerous Bioenergy Routes





Algal Biofuels in the Scientific Literature



- Published work includes photobioreactor design, lipid metabolism, genetic manipulation, and genomic analysis.
- Total work is relatively small, reflecting a fairly low level of research funding
- Papers on cellulosic ethanol outnumber algae papers by a factor of four
- Trend for cellulosic ethanol publications continues to rise, whereas algae papers appear to have declined in frequency since 2005.

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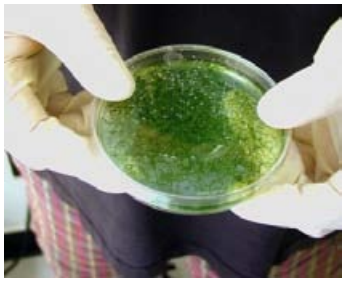
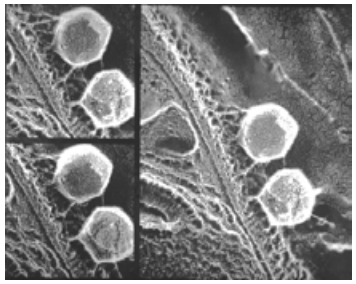
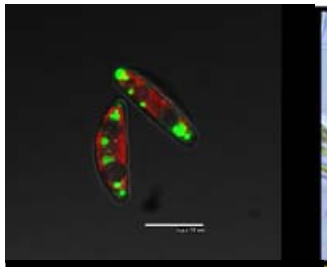
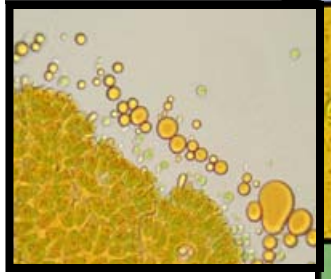
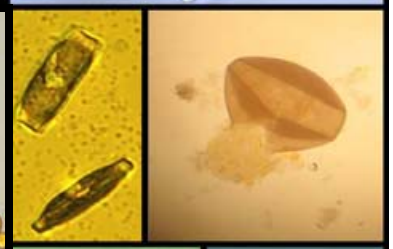
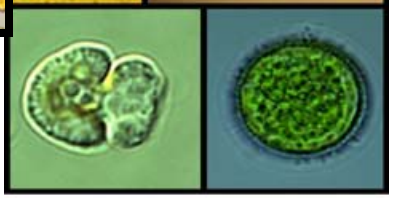




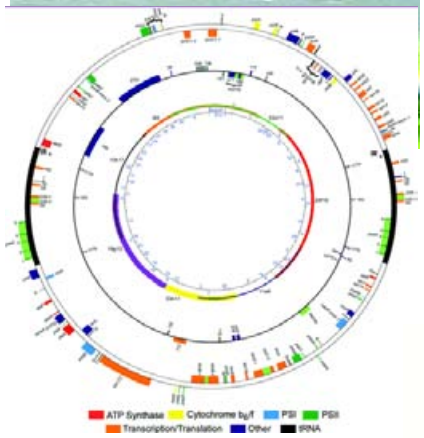


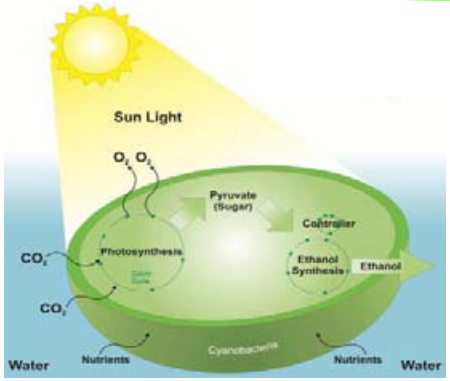


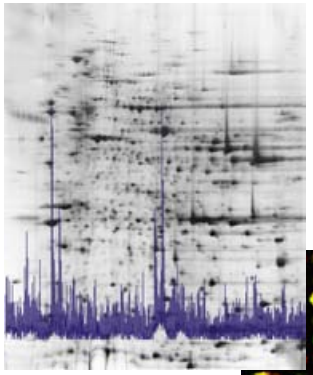


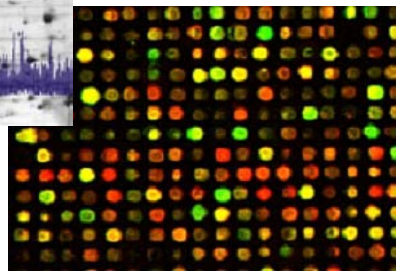


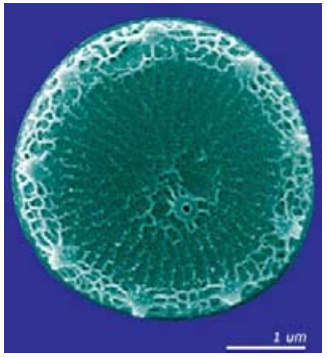
Algal Biology

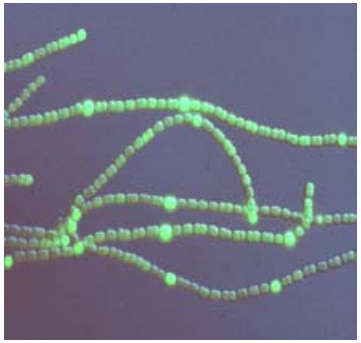












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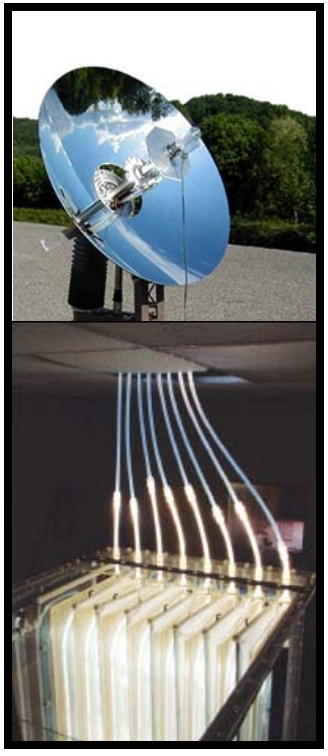

Cultivation

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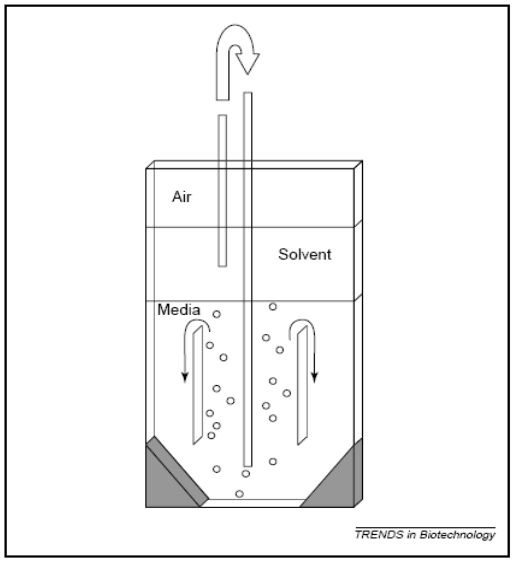
Electromechanical Disruption

Supercritical CO_2

Harvesting
Extraction



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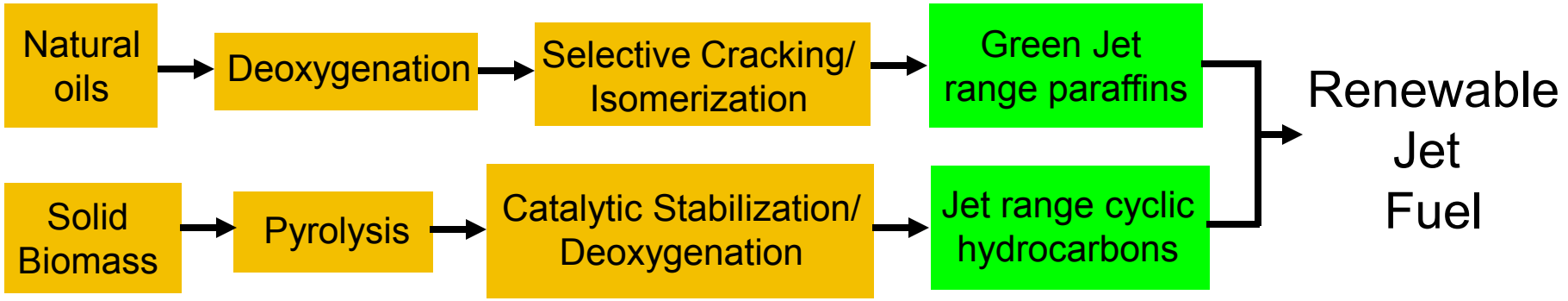

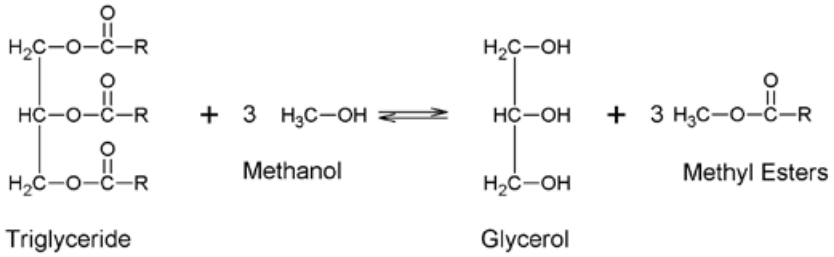

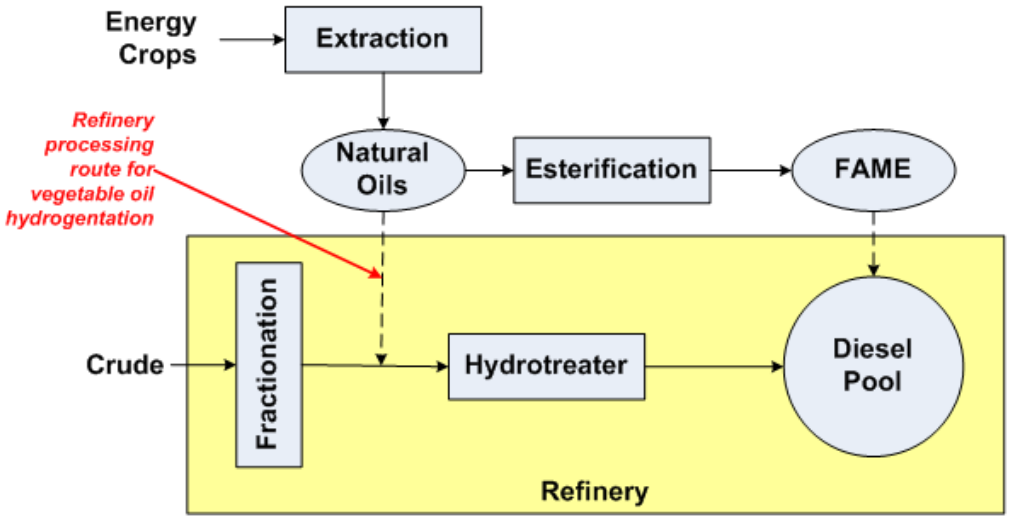

Fuel Conversion

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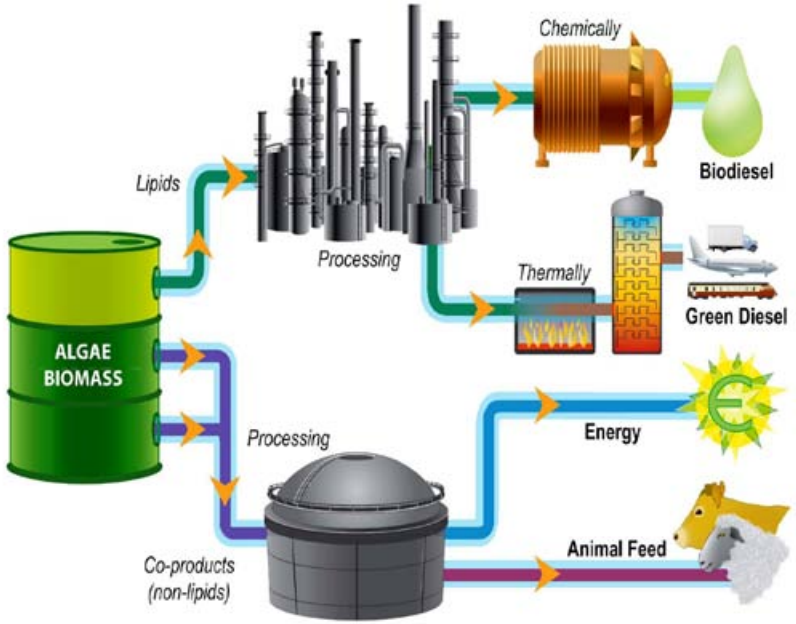
Co-products

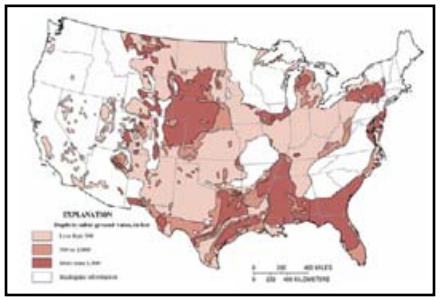
Carbohydrates
Protein
Fertilizer
Power
Methane
Oxygen

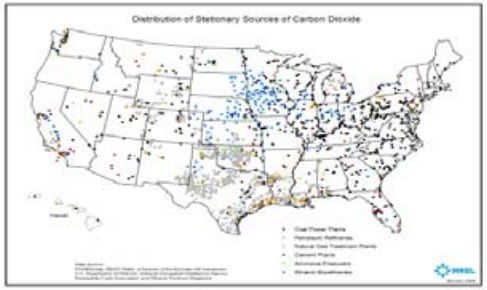


Source: Solix Biofuels

Systems Integration

Resources





Regulatory Policies

Current Activities/Funding Support for Algae Biofuels

• Government agencies (DOD, DOE) providing funding opportunities to research organizations working to perfect microalgae production.

• University-led algae programs are gaining strength

• Worldwide interest has prompted interest in microalgae production from the private sector.

• VCs investing in demonstration plants, feedstock development, and process improvement.

• **Venture Capital firms invested $280M in advanced biofuels (Q1-Q2 2008); $84 M for algae; by comparison, $4M invested for algae Q3 2007**

Current Federal Initiatives (DOD) – DARPA

- **Announcement:** BAA08-07 on 11/15/07.
  - Extension of BAA06-43 for conversion of agricultural feedstocks to JP-8 (EERC, UOP, GE Global)

- **Goal:** Development of a highly efficient system for low-cost algal oil production and optimizing its conversion to JP-8 jet fuel.
  - Commercialization plan to transition the technology to marketplace.
  - **Cost Targets:** Phase 1 (18 mo): <$2 gallon for TAG; Phase 2 (18 mo): <$1 gallon for TAG (or <$3 gallon finished cost at 50mmgy).

- **Teams:** Approximately 1/2 dozen teams submitted proposals.
  - Large defense contractors, Fortune 500 companies, start-ups, universities and government labs

    Tentative awards: General Atomics and SAIC

Current Federal Initiatives (DOD)–AFOSR/NREL

- **Funding:** AFOSR and NREL worked together to identify four (4) academic laboratories for the development of jet fuel from algae.

- **Recent Workshop in Arlington, VA:** 30-40 scientists, primarily from academia and National Labs met in Arlington, VA February, 2008 to:
  - Identify basic science approaches needed for controlling and/or augmenting algal lipid biosynthesis;
  - Identify specific problems/barriers that prevent achievement of cost-effective production of algal oil for jet fuel conversion;
  - Develop a basic science research “roadmap” from which recommendations can be made for future scientific funding opportunities within AFOSR.

Current Federal Initiatives (DOD) – USAF

- **Funding:** Funded a cooperative agreement between Arizona Public Service and DOE-Fossil Energy (FE)/National Energy Technology Laboratory (NETL)

- **Purpose:** Development and demonstration of a coal hydrogasification process for co-production of substitute natural gas and electricity with virtually no CO_2 emissions.

- **Algae Component:** Conducting field assessments of an algae farming technique to fix CO_2, as well as a conversion process to various liquid fuels.

Current Federal Initiatives (DOE) – Small Business Innovative Research SBIR/STTR Grants

Funds Awarded – Kent SeaTech:

- **Phase I** - culture microalgae that showed high capacity for CO2 fixation and to determine optimal conditions for producing rapid and consistent blooms of microalgae using nutrient-rich agricultural wastewaters.
- **Phase II (2005)** – optimize growing conditions (e.g., temperature, light, water depth and velocity, etc.), evaluations of a belt system to harvest algal biomass, and exploration of techniques to convert biomass to biofuels and coproducts.

- **Funds Awarded – Community Fuels:**
  - Phase I - evaluate two processes to produce biodiesel from algae and the use of agricultural waste to grow specific alga species.

Current Federal Initiatives (DOE) – Small Business Innovative Research SBIR/STTR Grants

- **FY2008 Solicitation:** Office of EERE administers SBIR grants under 9 categories, one of which is "Production of Biofuels from Biomass".

- **Subtopics:** One of four subtopics under this category is "Algae for Biodiesel".

- **Award Announcement – April 29, 2008:** 3 Phase I Awardees
  - ***Accent Laboratories, LLC*** *(New York)*: Developing a low-cost, high efficiency algae harvesting and dewatering technology.
  - ***Renewable Algal Energy, LLC*** *(Tennessee)*: Developing a low-cost method for growing and harvesting algae.
  - ***Touchstone Research Laboratory, Ltd.*** *(West Virginia)*: Developing a closed algae cultivation system that controls seasonal temperature fluctuations at a competitive cost

Current Federal Initiatives (DOE) – FY09 Small Business Innovative Research SBIR/STTR Grants

- **EERE – Microalgal Feedstock Production**
  - **Subtopic:** Harvesting algal biomass
- **Fossil Energy - Use of Algae for Fuels Production**
  - **Subtopic:** Concepts for Extracting Oil from Algae
  - **Subtopic:** Converting Algae-Derived Biodiesel into Aviation Fuels

Closed Nov. 20, 2008

Current Federal Initiatives (DOE) – Other Initiatives

- **International Network on Biofixation of CO_2 and Greenhouse Gas Abatement:** Organized based on an initiative by DOE – provide a forum for organizations interested in R&D of GHG abatement using microalgae

.

- **Office of Basic Energy Sciences:** BES supports basic research on biological conversion of solar energy to stored chemical energy (algae and cyanobacteria), but there are no open funding opportunities for algae.

- **Office of Biological and Environmental Research:** BER issued a FOA in Jan, 2008, for systems-level research to improve understanding of microbial regulatory and metabolic networks of hydrogen production.

- **DOE Joint Genome Institute:** Completed sequencing of ten algal genomes. The Community Sequencing Program (CSP) allows for the submission of sequencing projects to JGI.

Current Federal Initiatives – Government Labs

- **National Renewable Energy Laboratory:** Internally and externally funded algae research (LDRD, Strategic Initiatives, Chevron, C2B2)
- **Sandia National Laboratories:** Conduct research on algal biofuels emphasis on water resources and utilization (LDRD, DARPA, industry)
- **Pacific Northwest National Lab:** Performs basic and applied research in the area of microalgal biofuels. (LDRD, DOE NETL, Office of Science).
- **Oak Ridge Natl. Lab:** Cooperative research on a variety of production process challenges (Utah State University).
- **Los Alamos National Laboratory:** Applied research in the algal biofuels area; assist private sector (LDRD, CEHMM; General Atomics).
- **National Energy Technology Laboratory:** Recycling CO_2 emissions from power plants (APS).
- **NASA-Ames:** Greenspace Initiative: Algae in space - Nanoscale particles to harvest TAGs from algae (DOE)

University Research

- UC San Diego/Scripps
- Montana State University
- Old Dominion University
- Clemson University
- University of Washington
- University of Hawaii
- California Polytechnic State Univ.
- University of Maryland
- UC Berkeley ($500M BP Funding)
- Arizona State University ($1M BP)
- Utah State University
- Mississippi State University
- The Ohio State University
- Rutgers
- Stanford
- UCLA
- Colorado State University
- University of Minnesota
- New Mexico State University
- University of Colorado-Boulder
- University of Kansas
- University of Nebraska
- Auburn University
- Michigan State University
- Brooklyn College
- University of Texas – Austin
- Colorado School of Mines
- Princeton University
- Texas A&M
- Ohio University

Algae Biofuel Companies

A2BE Carbon Capture, LLC
Algae Biofuels
Algae Link
AlgaeWheel
Algenol
Algodyne
Algoil
AlgroSolutions
Aquaflow Bionomic
Aquatic Energy
Aurora BioFuels Inc.
Bionavitas
Blue Biofuels
Blue Marble Energy
Bodega Algae
Cequesta
Circle Biodiesel & Ethanol
Community Fuels
Diversified Energy
Energy Farms
Enhanced Biofuels & Technologies
General Atomics
Global Green Solutions
Green Star
Greenfuel Technologies Corp
GreenShift
GS Cleantech
HR Biopetroleum/Shell (Cellana)
IGV
Imperium Renewables
Infinifuel Biodiesel
Inventure Chemical
Kai BioEnergy
KAS
Kent SeaTech Corp.
Kwikpower
LiveFuels
Mighty Algae Biofuels
Oilfox
Organic Fuels
OriginOil
PetroAlgae
PetroSun
Phycal
Revolution Biofuels
Sapphire Energy
Seambiotic
SeaAg, Inc
Solazyme, Inc.
Solena
Solix Biofuels, Inc.
Sunrise Ridge Algae
Sunx Energy
Synthetic Genomics
Targeted Growth
Texas Clean Fuels
Trident Exploration/Menova
Valcent Products
W2 Energy
XL Renewables

2007 Energy Independence and Security Act (EISA)

- Increase availability of renewable energy that reduces GHG emissions
- Increases Renewable Fuel Standard (RFS) to 36 B gal by 2022.
- (Section 228) Requires Energy Secretary to present to Congress a report on the feasibility of microalgae as a feedstock for biofuels production
  - Status: Report has been released by OMB with comments

2008 Farm Bill

Title IX: reauthorizes, expands, and/or modifies existing programs, and creates new programs and initiatives to promote biofuels and cellulosic ethanol production.

Section 9003 - Biorefinery Assistance: Grants and Loan Guarantees for the commercialization of processes to convert *renewable biomass* to advanced biofuels.

Section 9005 – Bioenergy Program for Advanced Biofuels: Requires USDA to make direct payments to eligible producers to facilitate expansion of advanced biofuel production.

Section 9011 – Biomass Crop Assistance Program: Program to support the production of eligible crops for conversion to bioenergy. An *eligible crop* is any crop of *Renewable Biomass*, so algae is included.

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NBC NIGHTLY NEWS WITH BRIAN WILLIAMS

npr

nature.com

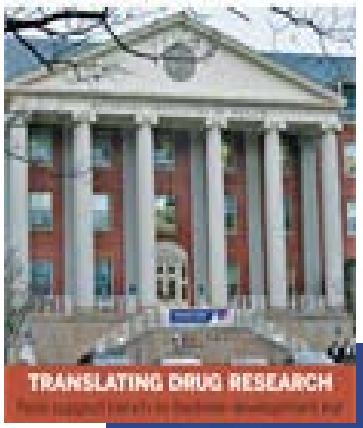
San Jose Mercury News

Esquire

AMERICAN PUBLIC MEDIA

HOUSTON CHRONICLE

C&EN



American RadioWorks

nature biotechnology

AP Associated Press

FT.com FINANCIAL TIMES

the Salina Journal

CNN

msnbc

PLENTY THE WORLD IN GREEN

THE WALL STREET JOURNAL.

Austin American-Statesman statesman.com

San Francisco Chronicle

CNNMoney.com

Previous Algal Biofuels Roadmapping Activities

- **Biofixation of CO_2 and Greenhouse Gas Abatement with Microalgae: Technology Roadmap (2003)**

- **Air Force Office of Scientific Research (AFOSR) Algae to Jet Fuel Workshop (2008)**

CO_2 Biofixation

Biofixation of CO_2 and Greenhouse Gas Abatement with Microalgae –Technology Roadmap

Prepared by:

John Benemann

Manager, International Network on Biofixation of CO2 and Greenhouse Gas Abatement with Microalgae

Submitted to the

U.S. Department of Energy

National Energy Technology Laboratory

and to the

Steering Committee of the International Network on Biofixation of CO2 and Greenhouse Gas Abatement with Microalgae

January 14, 2003

Algal Biofixation: Introduction

- U.S. DOE-NTEL supported the roadmap to provide an overview of the current state-of-the-art in the field
- Microalgae processes are “novel sequestration technologies” Carbon Sequestration Technology Roadmap (US DOE-NETL, 2002).
  - increase the speed and energy efficiency of CO_2 conversion processes
  - identify processes that produce high-value by-products to improve economics
- Roadmap provides a consensus of the R&D needed to develop microalgal processes that could abate hundreds of millions tons of fossil CO_2
- Considers only processes based on raceway, paddle wheel mixed, open ponds

Algal Biofixation: Processes

Four general multi-purpose processes that could meet these objectives (in a 5-10 year timeframe):

- Use of CO_2 supplemented (flue gas) municipal wastewater treatment process for co-production of methane
- Cultivation of microalgae on industrial and agricultural wastewaters for fertilizers, biofuels and animal feed co-products
- N_2-fixation and nutrient (nitrogen and phosphorus) recycling process with co-production of biofuels and biofertilizers
- Co-production of biofuels with large volume/higher value biopolymers and other chemicals

Algae Biofixation: R&D Issues

Algal Strain Selection and Genetics

- ***Ensuring mass culture stability is a central need***

  - Paradigm: *isolate strain, study attributes, scale-up process*

  - Preferred option: *isolate competitive strains, study physiological and genetic manipulations improvements to increase productivity and harvestability*

  - Complementary approach to achieving dominance: *produce large amounts of inoculum*

- ***Employing molecular techniques for accelerating bioprocess development is an essential component***

- ***Practical application of GMO technology not within timeframe of roadmap***

Algae Biofixation: R&D Issues

Microalgae Physiology and Productivity

- ***R&D of physiological responses to nutrient limitation***
- ***Responses to:***

  - detrimental O_2 accumulation

  - diurnal and seasonal temperature cycles

  - CO_2 and pH fluctuations

  - changing light intensities

- **Achieving high productivities (>100 tons/ha/yr)**

  - overcoming light saturation issues

  - addressing respiration which impacts productivity

Algae Biofixation: R&D Issues

Harvesting and Processing

- ***Developing, low cost harvesting has been the single most limiting factor in expanding algae applications***

  - bioflocculation and settling (challenge is how to control)

- ***Drying of algal sludge is not plausible (expensive)***

  - *burning biomass results in loss of fertilizer value*

  - thermochemical processing not recommended for algae

- ***Anaerobic digestion to produce biogas is the most readily applicable process***

  - some algae require pretreatment

Algae Biofixation: R&D Issues

Engineering Designs, Economic Analyses and Resource Potentials

- ***Large scale ponds do not present major uncertainties, however, the design and operation of unlined ponds needs study.***
- ***Engineering designs are useful for initial estimates of relative costs of various options.***
- ***Greatest need is to translate preliminary engineering designs/cost estimates into resource potentials (land, climate, water, etc)***

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

Purpose, Objective and Planned Outcome

- **AFOSR funds basic research; interested in the production of bio-based jet fuel using lipids (oil) derived from microalgae.**

- **Purpose:** to bring together a panel of outside algal experts to discuss a variety of basic science research issues related to microalgal oil production.

- **Objectives:**

  - identify specific hurdles that must be overcome to ultimately achieve cost-effective production of algal oil for jet fuel conversion;

  - address basic science research requirements needed to overcome these hurdles;

  - elucidate novel scientific approaches needed for developing a fundamental understanding of algal lipid biosynthesis and biomass cultivation principles.

    - **Outcome:** research guidance recommending future basic scientific funding opportunities for AFOSR and other federal agencies.

Workshop Speakers – Day 1

February 19, 2008

- Introduction and Goals – **Al Darzins**, NREL, and **Walt Kozumbo**, AFOSR
- Overview: Algae oil to biofuels – **John Benemann**, Benemann Assoc.
- Aquatic Species Program (ASP): Lessons learned – **Eric Jarvis**, NREL
- Bioprospecting for algae - **Juergen Polle***, Brooklyn College
- The Role of Culture Collections - **Jerry Brand**, Univ. Texas - Austin
- Sequencing of algae genomes - **Ginger Armbrust**, Univ. Washington
- Algal model systems – **Steve Mayfield**, The Scripps Research institute
- Algal growth and physiology - **Dick Sayre***, OSU
- General biochemistry of lipid pathways- **Wayne Riekhof**, Natl Jewish Med Ctr
- TAG pathways & oil accumulation in algae - **Christoph Benning***, MSU
- Growing algae in open ponds - **Ami Ben-Amotz**, Israel
- Wind, Sea and Algae - **Jonathan Trent**, NASA-Ames
- Strategic Road to Commercialization- Food and Fuel from Algae - **James Sears**, A2BE Carbon Capture

Workshop Speakers – Day 2

February 20, 2008

- Production of algae in conjunction with wastewater treatment – **Tryg Lundquist**, California Poly
- Closed photobioreactors - **Qiang Hu**, Arizona State University
- Power plant emissions to biofuels, **Xiaolei Sun**, Arizona Public Service
- Development of algae genetic tools – **Mark Hildebrand***, Scripps Institute of Oceanography
- Algal Photosynthesis- **Charles Dismukes***, Princeton University
- Technoeconomic analysis of oil production - **Byard Wood**, Utah State University
- Biosafety, environmental and regulatory issues – **Rachel Lattimore**, Arent Fox, LLP

http://www.nrel.gov/biomass/algal_oil_workshop.html

Break-out Sessions

A. Strain Research I – Isolation, selection, and characterization
Discussion Lead: Juergen Polle, Brooklyn College

B. Cultivation research – Growth requirements, systems engineering
Discussion Lead: Tryg Lundquist, California Poly

C. Photosynthesis research – Efficiency, fundamental biology
Discussion Lead: Maria Ghirardi, NREL

D. Strain Research II- Lipid pathway analysis, genetic/molecular tools
Discussion Lead: Steve Mayfield. Scripps Research Institute

E. Process research – Harvesting, extraction, lipid upgrading
Discussion Lead: David Brune, Clemson University

F. Technoeconomics – LCA, production costs, impact of co-products
Discussion Lead: Byard Wood, Utah State University

Strain Research I

- **Publically available strain database and resource center**
  - growth rates, temp. ranges, lipid content/composition, general physiology
- **Isolation of novel strains**
  - Issue: use of culture collection strains vs diversity in environment
  - Consensus exists for the need to isolate novel (biofuels/feedstock producing) strains from a variety of unique habitats
  - Needs of the algae community are diverse; max. genetic diversity, models strains, and outdoor applications
- **Model organism(s)**
  - Issue: one (or few) vs many models systems
  - Consensus: in addition to *C. reinhardtii*, multiple model organisms should be pursued
  - Selection criteria: lipid content/profiles; rapid growth productivity; available genetics; robust in mass culture

Strain Research II

- **General theme: Develop specific model species for focused research and survey a broad range of species to use as a source of genes for modification.**
  - Ramp up sequencing of algal genomes
  - 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 (transformation methods, selection, promoters, gene replacement/silencing, breeding approaches)

Photosynthesis

- **Rates of photosynthesis are limiting for oil production given the reaction generates NADPH and ATP required for lipid biosynthesis.**

- **Solar conversion efficiency is <2% (20% of expected maximum). Main light adsorption limitations to be addressed:**
  - *identify natural or engineered organisms that have the highest 1º energy storage capacity (ATP and NADPH) at levels that support optimal growth rate throughout the daily solar cycle.*
  - *generate a database that correlates photosynthetic, light-to-biomass conversion efficiencies and growth rates from a variety of organisms under solar and solar-simulated conditions*
  - *photosynthetic e- transport becomes limiting when NADPH/ATP are not being consumed – important for lipid producing algae since NADPH/ATP ratios required for lipid synthesis is much higher than required for CO_2 fixation – need availability of organisms in which ratio of cellular reductants to ATP can be controlled.*

Summary and Future Outlook

- Production of lipid-based fuels from algae have been demonstrated.
- Algae can be grown and harvested; lipids can be extracted and converted to biodiesel or other transportation fuels-hydrogen & ethanol
- Biofuels from algae is possible, but can it be made economically and at a scale sufficient to help contribute to U.S. fuel demand?
- The potential of algal biofuels is significant, but a greater understanding of the underlying principles is necessary before commercial scale-up is feasible.
- Fundamental/applied R&D will be needed before algal-based fuels can be produced economically enough to be cost-competitive with petroleum based fuels.
- This will require coordinated support from relevant government agencies, private sector, academia, and all interested stakeholders.