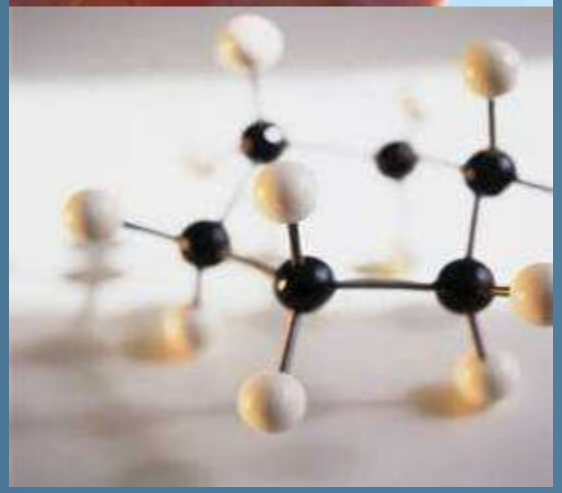


Algae Biofuels Technology

Office Of Biomass Program
Energy Efficiency and Renewable Energy

Jonathan L. Male
May 27, 2010

Biomass Program Mission and Objectives

Develop and transform our renewable and abundant, non-food, biomass resources into sustainable, cost-competitive, high-performance biofuels, bioproducts and biopower.

Focus on targeted research, development, and demonstration

- Through public and private partnerships
- Deploy in integrated biorefineries

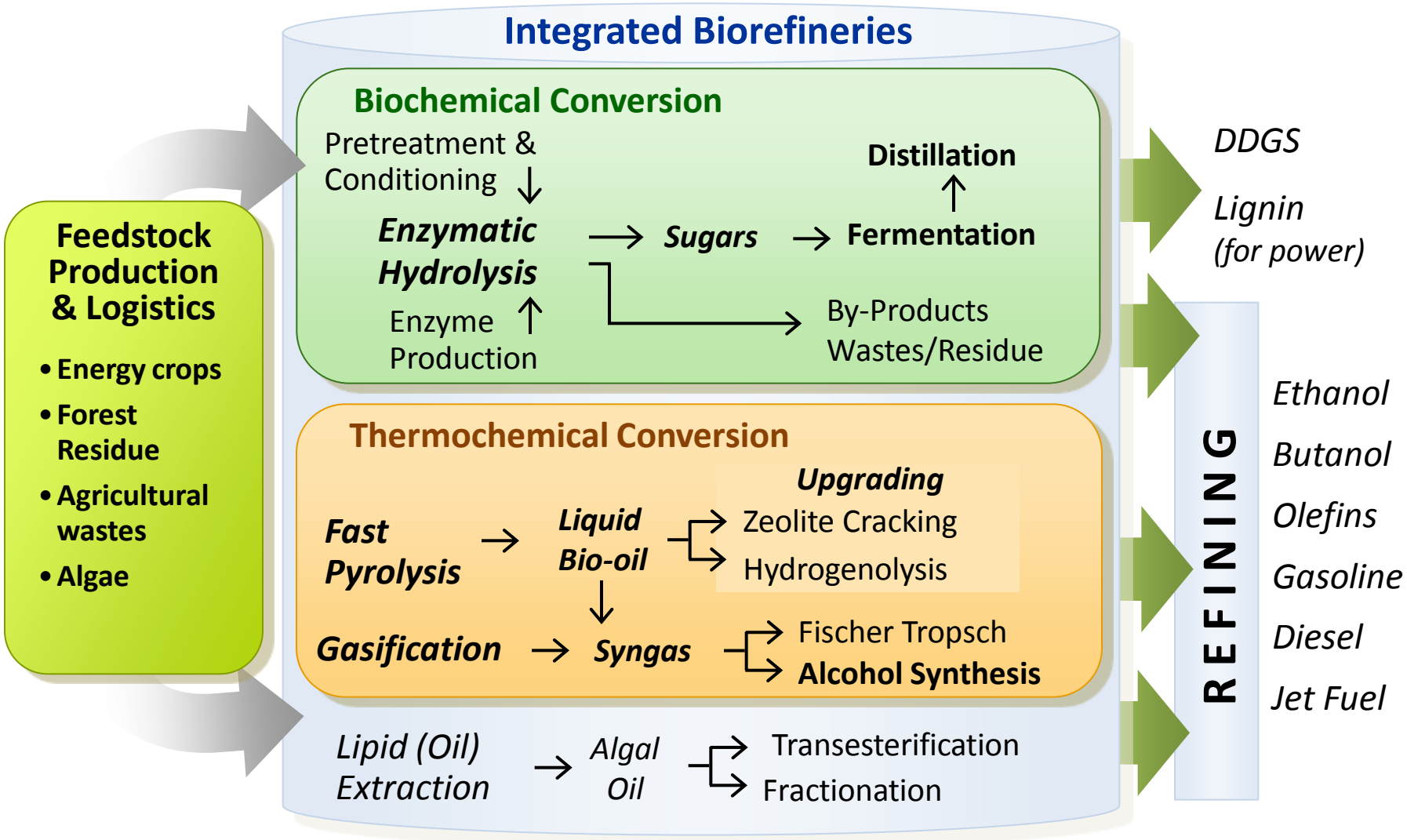
Biomass Program

- **Make cellulosic ethanol cost competitive, at a modeled cost for mature technology of $1.76/gallon by 2017**
- **Help create an environment conducive to maximizing production and use of biofuels- 21 billion gallons of advanced biofuels per year by 2022 (EISA)**

Feedstocks | **Conversion** | **Integrated Biorefineries** | **Biofuels Infrastructure**

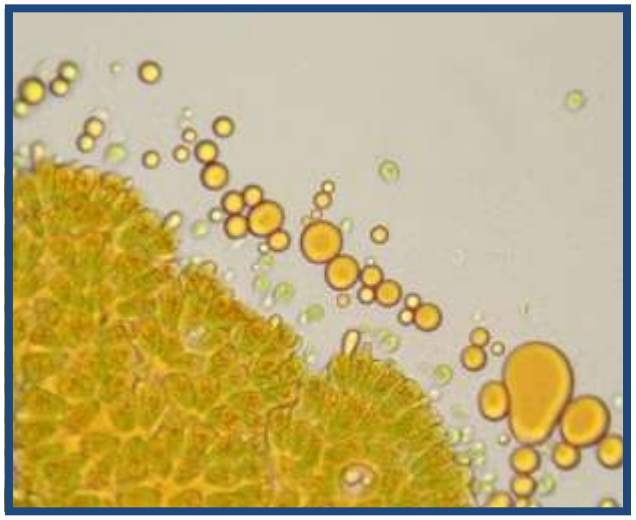
Sustainability & Analysis

Exploring Routes to Convert Biomass



Research on multiple conversion pathways and hybrid pathways aims to improve the efficiency and economics of biofuels production.

Why Algae? Supply



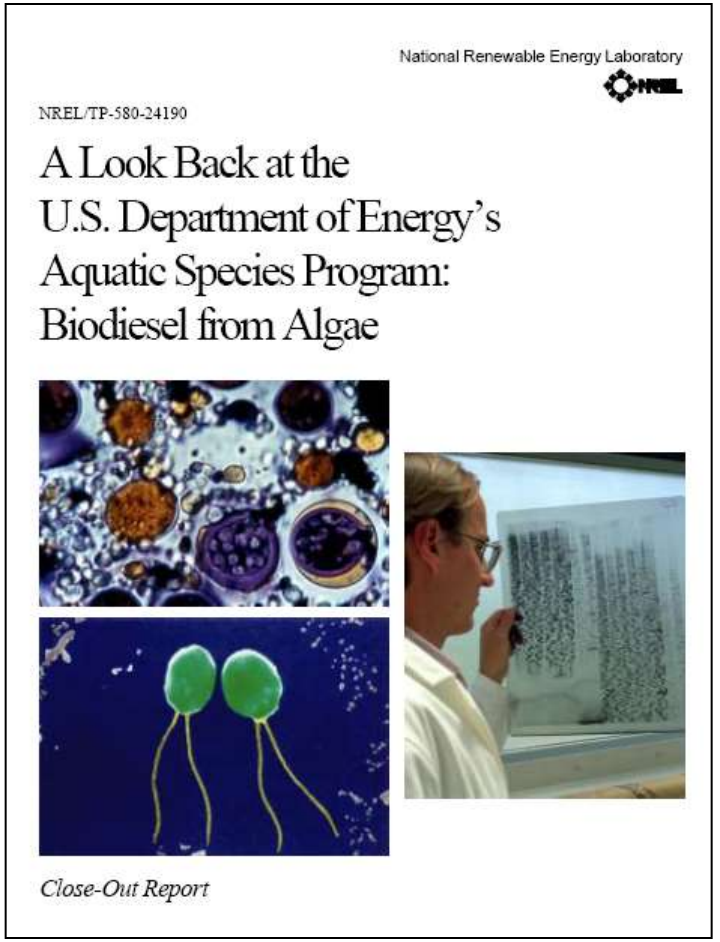
- Algae may produce more lipids (plant oils) per acre than other plants -- *potentially 2x - 20x*
  - Lipids are the preferred starting point to make diesel or jet fuel from biomass
- Algae cultivation may utilize:
  - marginal, non-arable land
  - saline/brackish water
  - large waste CO_2 vent resources
- Minimizing competition with food, feed, or fiber

DOE Aquatic Species Program

1978-1996 $25M

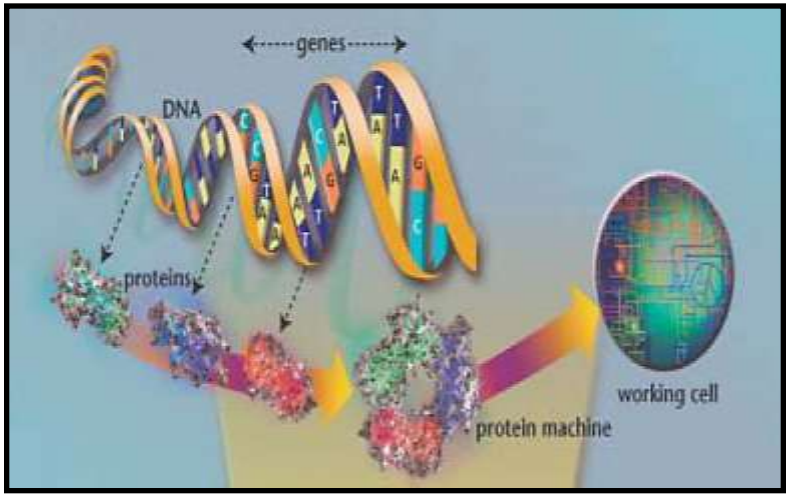
Excerpt from ASP Close-Out Report (1998)

In 1995, DOE made the difficult decision to eliminate funding for algae research within the Biofuels Program … [T]his report should be seen not as an ending, but as a beginning. When the time is right, we fully expect to see renewed interest in algae as a source of fuels and other chemicals. The highlights presented here should serve as a foundation for these future efforts.



What's Changed Since 1996?

- Volatile Petroleum Distillate Pricing
  - Crude oil prices have seen record highs ($147/barrel)
- Technology has improved dramatically
  - New photobioreactor designs and advances in material science
  - Explosion in biotechnology -- advances in metabolic engineering and systems biology
- Greater emphasis on energy security and CO_2 capture, GHG reduction, etc



DOE's Office of Science Joint Genome Institute recently published the genome sequence of *Chlamydomonas reinhardii* (Science, 318:245-50, 2007) and has 4 additional algal species currently in its pipeline resulting from user-initiated submissions to JGI's Community Sequencing Program.

Algal Systems Technical Barriers

Algal Cultivation

- Bioreactor design
  - Temperature control
  - Invasion and fouling
- Starting species
  - Growth rate
  - Oil content & FA profile
- Nutrient requirements
  - CO_2 and H_2O sources
- Fundamental Algal Biology

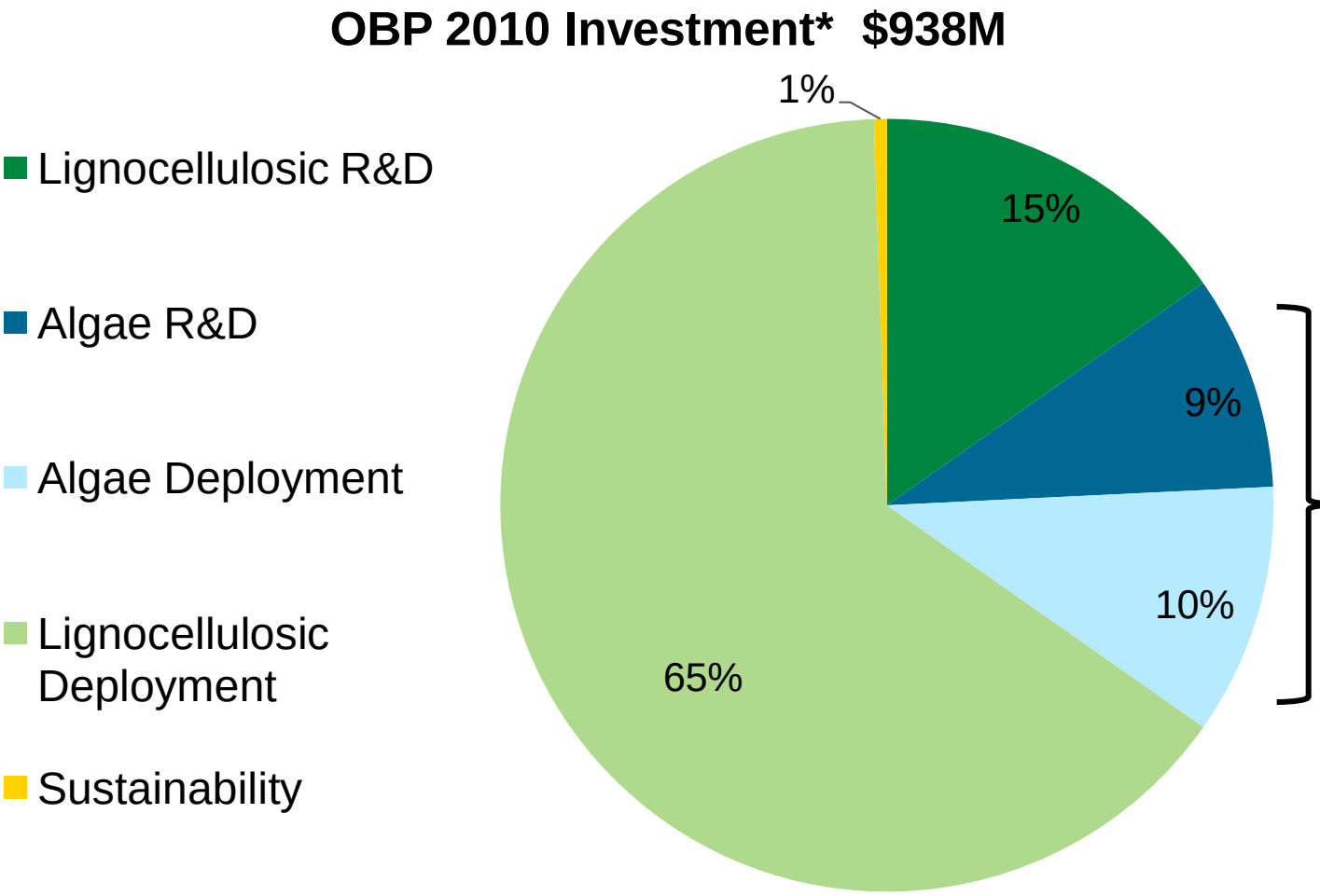
Oil (Lipid) Recovery

- De-watering methods
- Lipid extraction
- Purification

Fuel Production

- Process optimization
- Fuel characteristics
- Engine testing (ASTM)

Biomass Program Budget



The 2010 investment in algae totals more than $180M and includes:

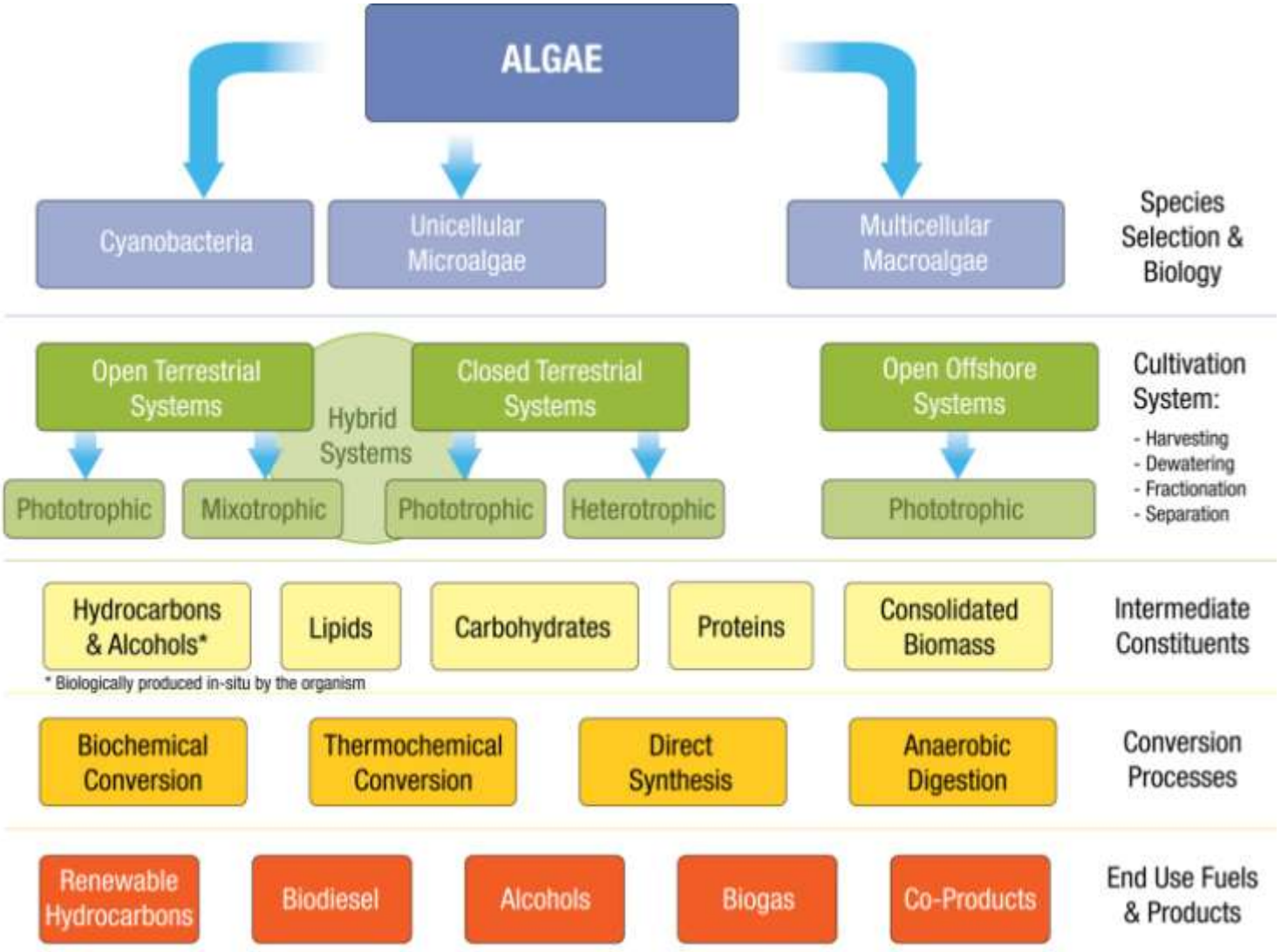
- $35M for algae R&D, as directed by Congress
- $49M for the NAABB consortium
- $50M for the Sapphire to deploy open pond algal biofuel system
- $25M for the Algenol to pilot an photobioreactor algal biofuel system
- $22M for Solazymes to pilot a heterotrophic algal biofuel system

*Includes regular FY2010 appropriations and 2009 ARRA funds

DOE Algal Biofuels Efforts

- DOE Office of Biomass Program is establishing an "Advanced Biofuels Initiative"
- An element will be the "Algal Biofuels Pathway"
- Draft "National Algal Biofuels Technology Roadmap" released for comments in 2009
  - Stakeholder workshop held Dec. 2008
  - Anticipate 4 major R&D and analysis areas:
    - Basic algal biology
    - Cultivation and process research
    - Production/integrated scale up
    - Sustainability and economic analysis

Research Planning: Algal Biofuels



Recent DOE-Biomass Algae Projects

- 3 University-based algae projects
  - University of Georgia – livestock waste as algae nutrient
  - Montana State & Utah State Universities - extremophilic algae
  - Scripps Oceanographic Institute- diatom lipids
- DOE National Laboratory involvement
  - Techno-economic modeling (Sandia and NREL)
  - Resource assessment (Pacific Northwest National Lab)
  - Algae biodiesel production (Los Alamos National Lab)
- Algal biofuels consortium (ARRA)
- 3 Integrated Biorefinery Projects (ARRA)
- 35 million additional FY10 funds TBD
- International Collaborations
  - US-Israel Partnership (Sandia, NREL, CEHMM, Seambiotic)- process modeling, life-cycle assessment
  - US-Canada Partnership (Sandia, NREL, NRCAN)- process modeling, strain optimization for flue gas CO2

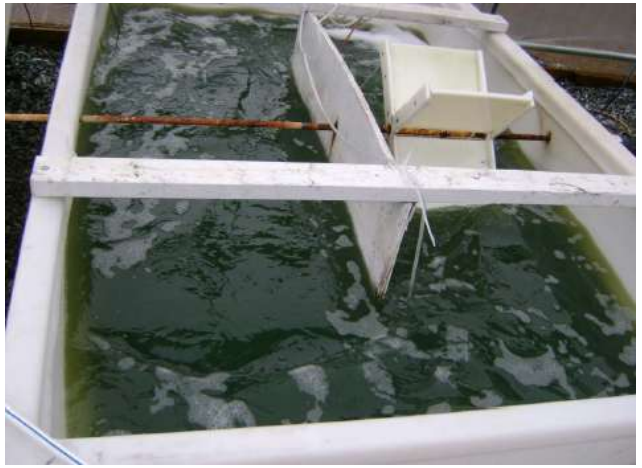


Photo courtesy of Dr. Das (U. Georgia)

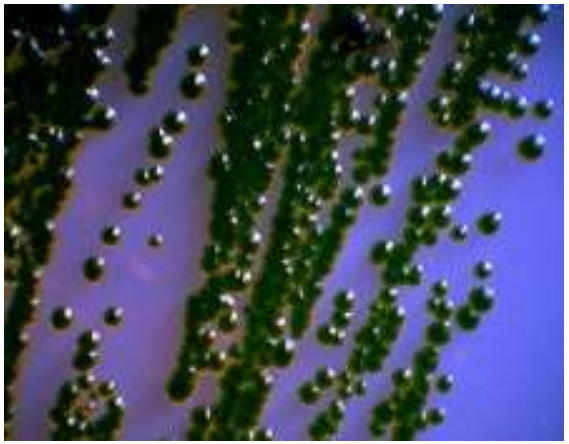


Photo courtesy of Dr. Peyton (Montana St.)

Locations of Integrated Biorefinery Projects

For more information, visit: http://www.eere.energy.gov/biomass/integrated_biorefineries.html

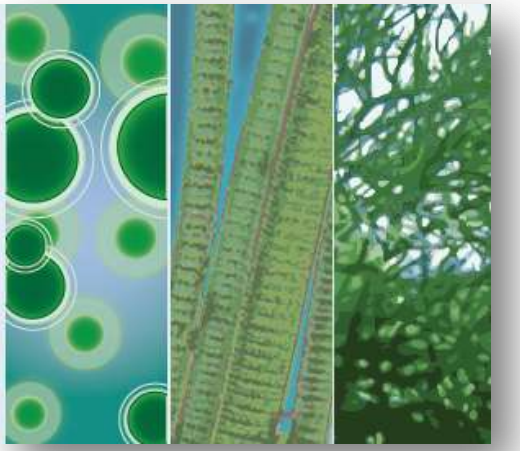
National Alliance for Advanced Biofuels and Bioproducts

Project Objective – Investigate and integrate multiple approaches to meet the central challenges of feedstock production, handling logistics, and conversion in order to lower costs of algal biofuels.

Funding - 3 year effort Recovery Act/DOE Funding $49M
Cost Share $25M
Total $74M

Development and Commercialization Value Chain

Expectations for the NAABB



- The Biomass Program supports the national scale deployment of new bioenergy technologies.
- Deployment of new technology is risky and costly – the Biomass Program invests heavily understanding and modeling bioenergy pathways and processes to better understand the risks and costs.
- Our expectations of this consortium are clear: *Do the research and generate the data necessary to find out what has changed in the intervening years, and set and evaluate aggressive, cost-driven targets for multiple algal biofuel pathways.*
- ***Develop the science and technology necessary to significantly increase production of algal biomass and lipids, efficiently harvest and extract algae and algal products, and establish valuable conversion routes to fuels and co-products.***

Information Resources

- Office of Biomass Program, http://www1.eere.energy.gov/biomass/
- EERE Info Center - www1.eere.energy.gov/informationcenter
- Alternative Fuels Data Center - http://www.eere.energy.gov/afdc/fuels/ethanol.html
- Bioenergy Feedstock Information Network - http://bioenergy.ornl.gov/
- Biomass R&D Initiative – www.biomass.govtools.us
- Grant Solicitations - www.grants.gov
- Office of Science - http://www.er.doe.gov/
- Biomass 2010 Conference Presentations- http://www1.eere.energy.gov/biomass/biomass2010/
- National Alliance for Advanced Biofuels and Bioproducts - http://www.naabb.org

Appendix

Fuels From Algae

Petroleum Refinery

60% Lipids

40% Carbohydrates and Protein

Cellulosic Biorefinery

Ethanol

Biodiesel

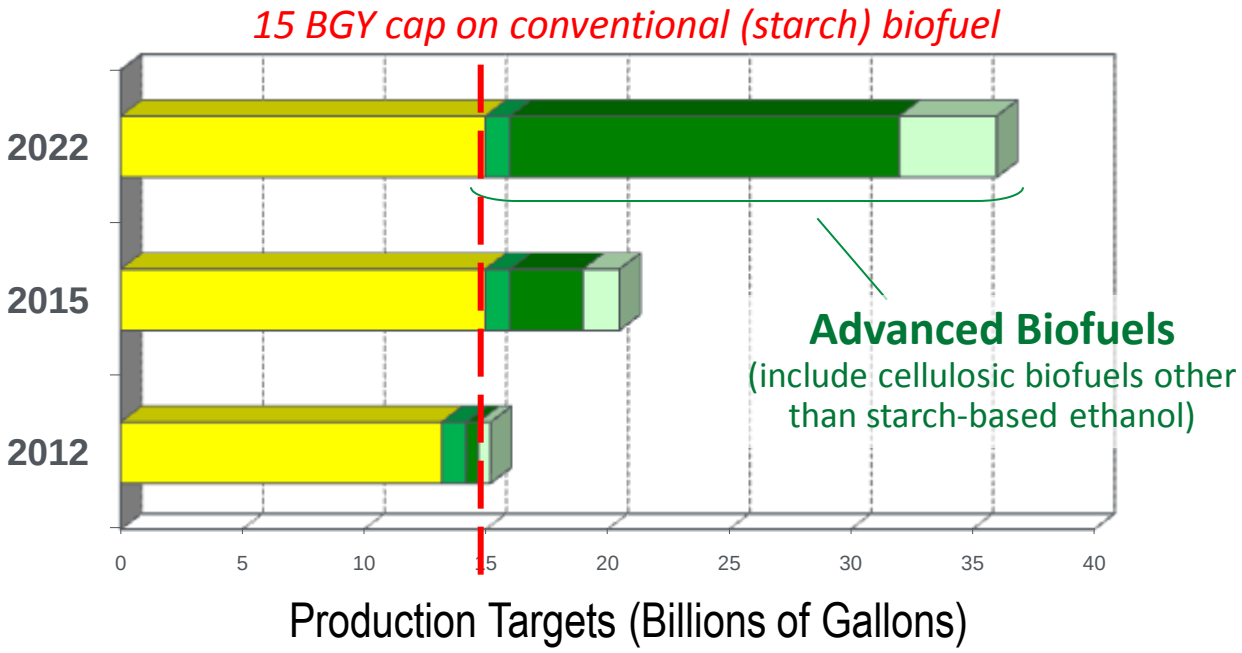
Green Diesel

Jet Fuel (Jet A or JP-8)

EISA Mandated Biofuel Production Targets

Renewable Fuel Standard (RFS2)

- Conventional (Starch) Biofuel
- Biomass-based diesel
- Cellulosic Biofuels
- Other Advanced Biofuels

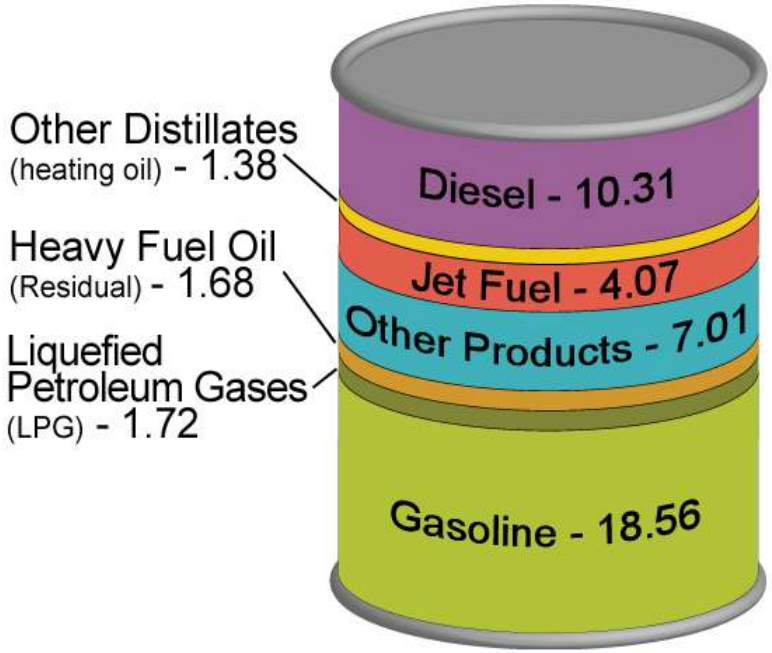


EISA defines ***Cellulosic Biofuel*** as "renewable fuel derived from any cellulose, hemicellulose, or lignin that is derived from renewable biomass and that has lifecycle greenhouse gas emissions…that are *at least 60 percent less* than baseline lifecycle greenhouse gas emissions." The EPA interprets this to include cellulosic-based diesel fuel.

EISA defines Advanced ***Biofuel*** as "renewable fuel, other than ethanol derived from corn starch, that has lifecycle greenhouse gas emissions…that are *at least 50 percent less* than baseline lifecycle greenhouse gas emissions." This includes biomass-based diesel, cellulosic biofuels, and other advanced fuels such as sugarcane-based ethanol.

Rationale for Advanced Biofuels

Products Made from a Barrel of Crude Oil (Gallons)



U.S. Diesel Outlook
(EIA AEO 2009 Reference Case for 2030)

- 75 billion gal/yr
  - 0.5 billion gal/yr biodiesel production (2007)

U.S. Jet Fuel Outlook
(EIA AEO 2009 Reference Case for 2030)

- 31 billion gal/yr

- **Cellulosic ethanol displaces light duty gasoline fraction only**
- **Heavy duty/diesel and jet fuel substitutes are needed to displace other components of the barrel**

Source: Energy Information Administration, "Petroleum Explained" and AEO2009, Updated (post-ARRA), Reference Case.

ASP Accomplishments

- 3,000 strains of algae collected and screened;
- Advances in applied biology and design of algae production systems achieved
- 1,000m^2 open pond facility operated in Roswell, New Mexico for one year
- Final cost estimates for algal lipids $40 - $70 per bbl oil in $1980 (Benemann and Oswald, 1996). Our initial estimates are that this translates to $90 - $160 per bbl oil in $2008 (EIA Annual Energy Report)
- Final report is still reference --important resource for algae researchers worldwide
- Main authors are now recognized leaders in this field

Paul Roessler
Synthetic Genomics
Venture with Exxon-Mobil

Joe Weissman
Exxon-Mobil
Venture with Synthetic Genomics

John Benemann
Independent Consultant

John Sheehan
Science Program Coordinator
U. Minnesota
Institute on the Environment

Advanced Biofuels Implications: Algal Oils

Crop	Oil Yield (gal/ac/yr)
Soybean	48
Camelina	62
Sunflower	102
Jatropha	202
Oil Palm	635
Microalgae	1000-4000

Adapted from Christi (2007), as cited in the National Algal Biofuels Technology Roadmap.

Cyclotella

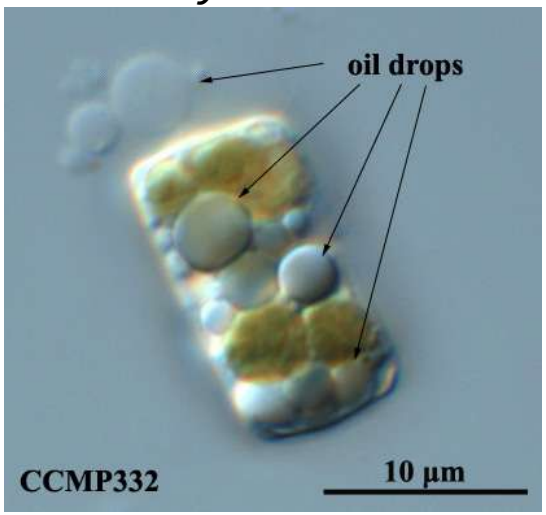


Photo Source: R. Andersen/CCMP

Triacylglyceride (TAG)

Fatty Acid (FA)

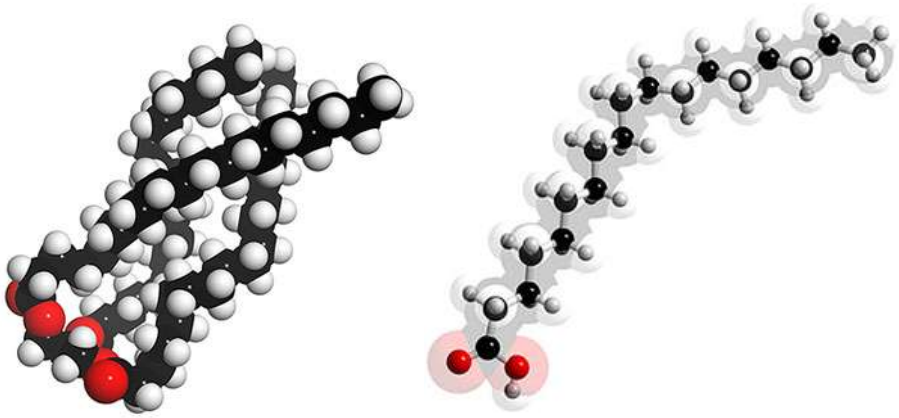


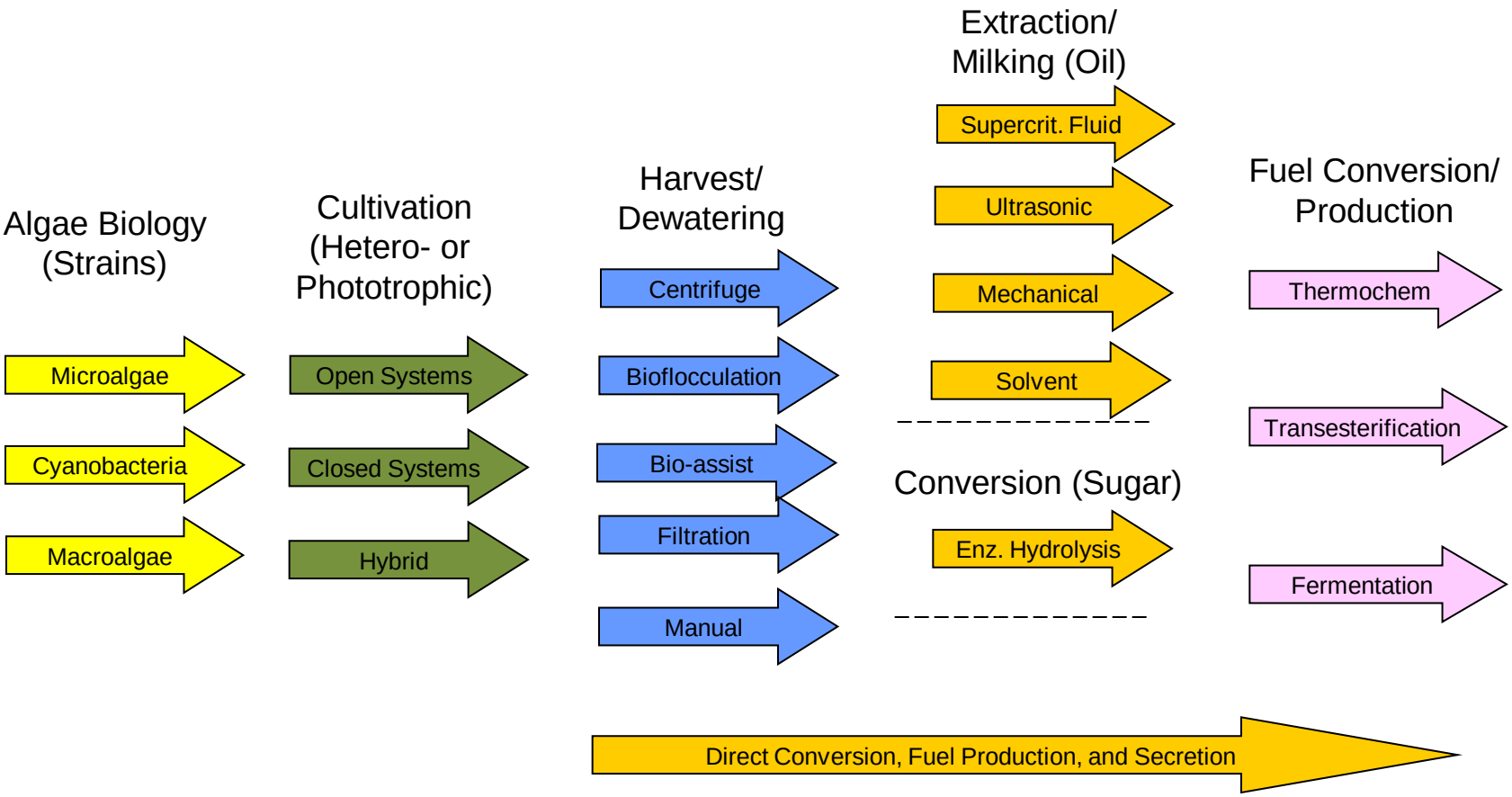
Photo Source: 3dChem Website

Commercial-Scale Cultivation

Raceway Ponds
Cyanotech, Hawaii

Outdoor Photobioreactor
Arizona State University

Diverse Process Options



New Integrated Biorefineries Using Algae

Pilot Scale Biorefinery

Performer	Location	DOE Award*	Feedstock Type	Conversion Technology	Fuel / Capacity**	Status
Algenol Biofuels, Inc.	Freeport, TX	$25M	Co_2 , Algae and Seawater	Closed Bioreactor	>100,000 gals Ethanol/year	Phase 1 award
Solazyme, Inc.	Riverside, PA	$21.7	Sugar Fed Algae, Sucrose (from cane), Municipal Green Waste, Switchgrass	Biochemical Conversion Process	300K gals/yr of Purified Algal Oil Product: Biodiesel and Renewable Diesel	Phase 1 Award for engineering design and environmental permitting.

Demonstration Scale Biorefinery

Performer	Location	DOE Award*	Feedstock Type	Conversion Technology	Fuel / Capacity**	Status
Sapphire Energy, Inc.	Columbus, NM	$50M	Co_2 and Algae	Dynamic Fuels, LLC refining process	IM gals/year of Jet Fuel and Diesel	Demonstration Phase 1 Award for engineering design and environmental permitting.

*Award amounts still under negotiation.

**Fuel capacities are based on performers estimates.

The NAABB Targets for a Viable Algal Biofuels Industry

- **Increased Algal Production**
  - >50% lipid/hydrocarbon dry weight
  - >20 gdw/m^2/day from pond cultivation
  - 1-2 gdw/L from bioreactors
- **Efficient Harvesting and Extraction**
  - 5000 gal/day processing
  - 15 gal/day lipid extraction
  - $0.51 /std barrel/day
- **Marketable Co-products**
  - Animal feed development and testing
  - Glycerol = $80/ton
  - Lipid extracted algae = $250-1000 / ton
- **Affordable Fuel**
  - <$0.40 / algal processing
  - <$2.10 / gal lipid

National Alliance for Advanced Biofuels and Bioproducts

Donald Danforth Plant Center, lead institution

National Laboratories

- Los Alamos National Laboratory
- Pacific Northwest National Laboratory

Universities

- Brooklyn College
- Colorado State University
- New Mexico State University
- Texas AgriLife Research (TAMU)
- Texas A&M University System
- University of Arizona
- University of California Los Angeles
- University of California San Diego
- University of California Davis
- University of Washington
- Washington University, St. Louis
- Washington State University

Industries

- AXI
- Allied Minds
- Catilin
- Diversified Energy
- Eldorado Biofuels
- Genifuel
- HR Biopetroleum
- Inventure
- Kai BioEnergy
- Palmer Labs
- Pratt & Whitney
- Solix Biofuels
- Targeted Growth
- Terrabon
- UOP

Subcontractors: Clarkson University, Center of Excellence for Hazardous Materials Management, Iowa State University, North Carolina State University, University of Pennsylvania, University of Texas