NREL National Renewable Energy Laboratory
Innovation for Our Energy Future

Algal Biofuels: Ponds and Promises

13th Annual Symposium on Industrial and Fermentation Microbiology

Philip T. Pienkos, Ph.D.
Principal Research Supervisor
National Bioenergy Center

May 1, 2009

NREL/PR-510-45822

Biofuel Challenges: Energy Density

Cellulosic ethanol addresses the gasoline market

- U.S. gasoline: 140 billion gallons/year

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

Energy Densities

Ethanol	Gasoline	Biodiesel	Diesel/Jet Fuel
76,330 Btu/gal	116,090 Btu/gal	118,170 Btu/gal	128,545/135,000 Btu/gal

Biodiesel Dilemma: TAGs from current oilseed crops cannot come close to meeting U.S. diesel demand (44 billion gal/year)

- Soy oil crop (2.75 B gal; 2006) could only replace ~4% of U.S. demand
- Cost of biodiesel feedstock high (~$2.50/gallon for soybean oil)
- Vegetable oils must compete with food market
- 2.5B gallon capacity in US, but only 700M gallons produced in 2008

Why Fuels from Algae?

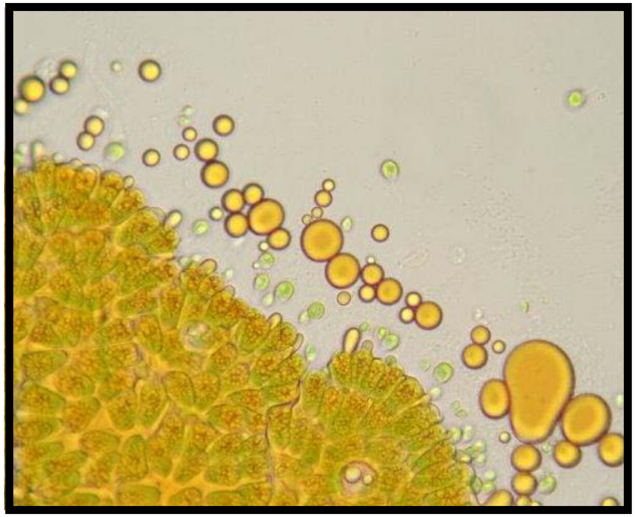


Image courtesy: Q. Hu, ASU

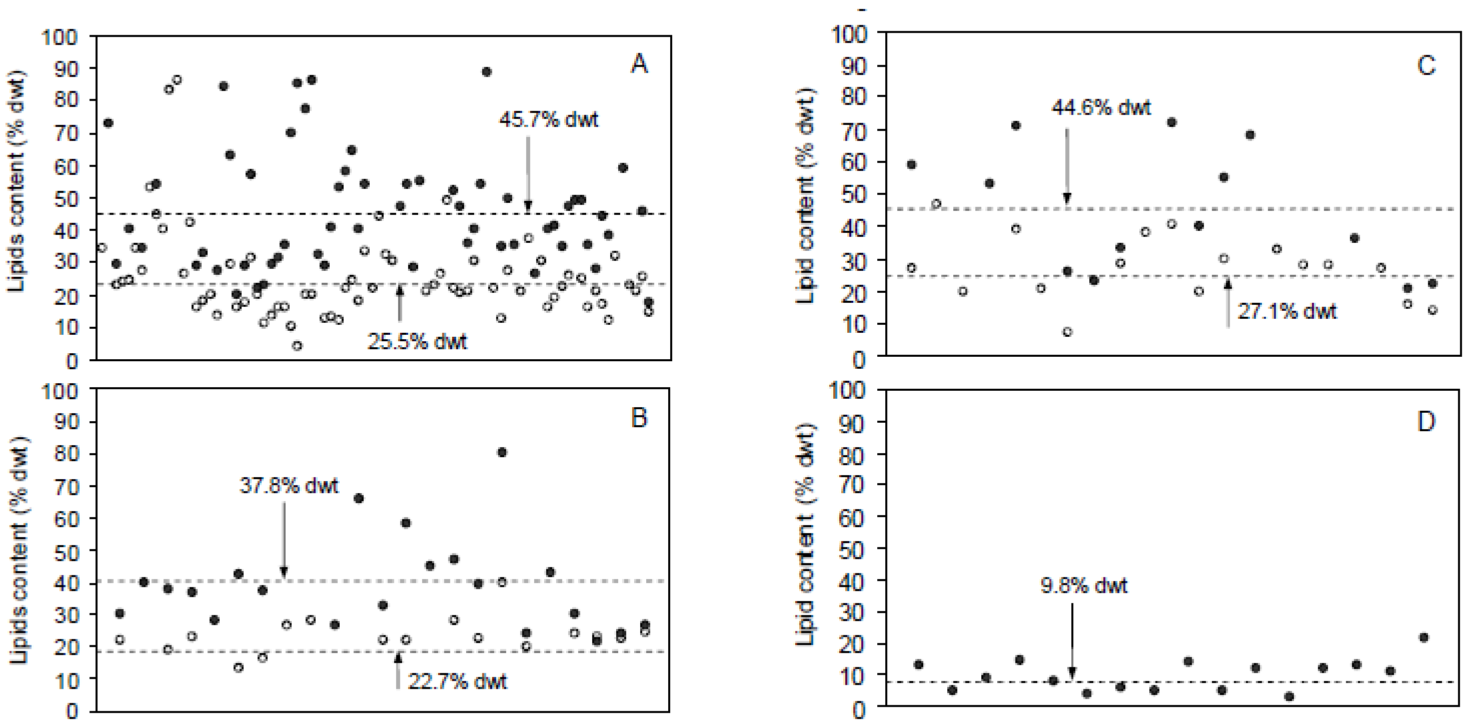
Image courtesy: A. Ben-Amotz, Seambiotic

- Algae can produce more lipids per acre than other plants -- *potentially 10x - 100x*
- Can use marginal, non-arable land
- Can use saline/brackish water
- No competition with food, feed, or fiber
- Can utilize large waste CO_2 resources
- Potential to displace significant amount of U.S. diesel and jet fuel usage
- An algal biorefinery could produce oils, protein, and carbohydrates and a variety of other products

Microalgae

- Unicellular photosynthetic microorganisms
- Thrive in diverse ecosystems
- >40,000 species identified
- Span wide range of taxonomic divisions
  - Cyanophyta (cyanobacteria)
  - Prochlorphyta
  - Glaucophyta
  - Rhodophyta (red algae)
  - Cryptophyta (cryptomonads)
  - Chlorophyta (green algae)
  - Euglenophyta
  - Chloroarachniophyta
  - Pyrrophyta (dinoflaggellates)
  - Chromophyta (heterokonts)

Lipid Accumulation in Microalgae

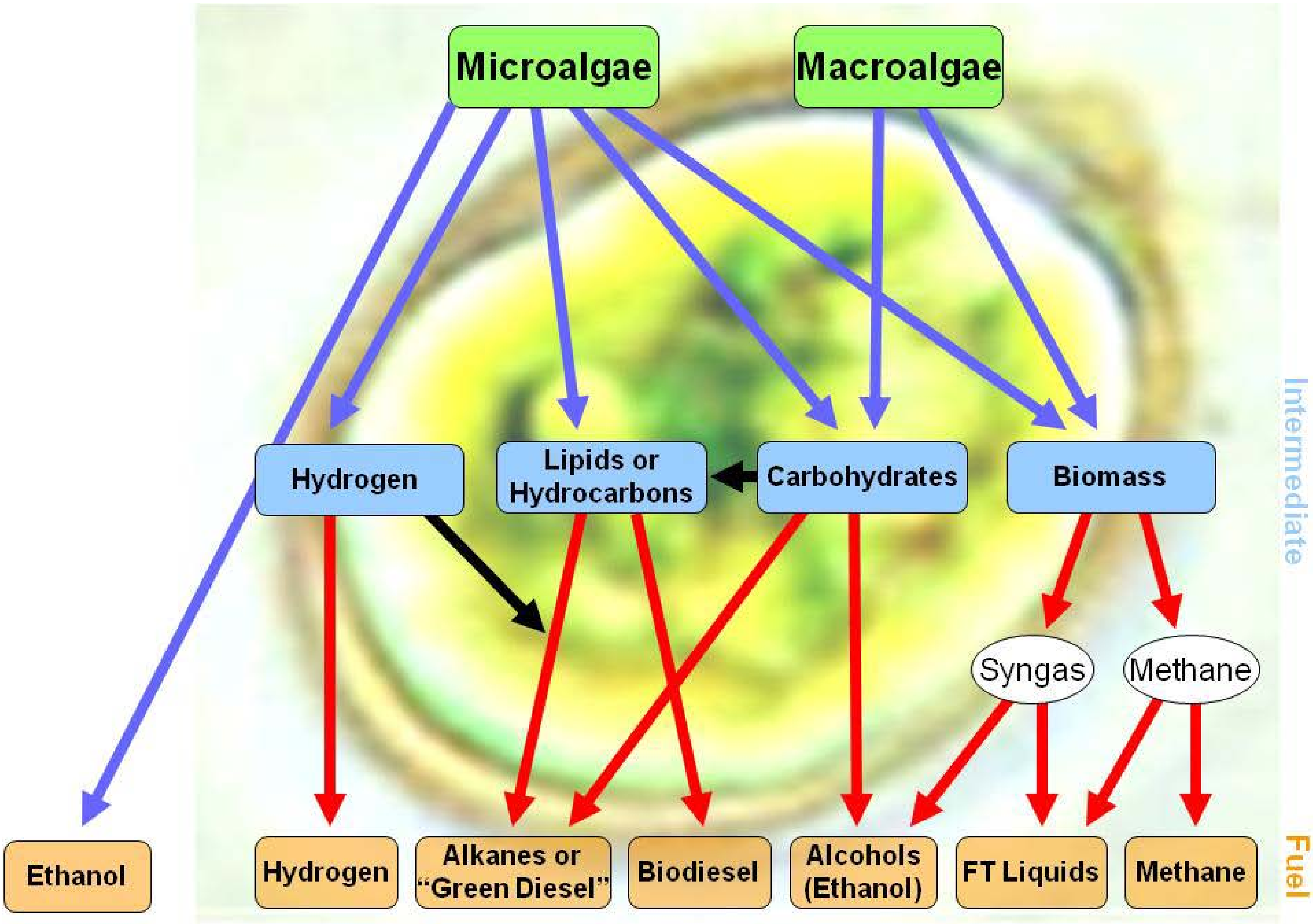


(A) Green microalgae; (B) diatoms; (C) oleaginous species/strains from other eukaryotic algal taxa; and (D) cyanobacteria. Open circles: Cellular lipid contents obtained under normal growth or nitrogen-replete conditions. Closed circles: Cellular lipid contents obtained under nitrogen depleted or other stress conditions.

Lipid Yields

Crop	Oil Yield Gallons/acre
Corn	18
Cotton	35
Soybean	48
Mustard seed	61
Sunflower	102
Rapeseed	127
Jatropha	202
Oil palm	635
Algae	“10,000”

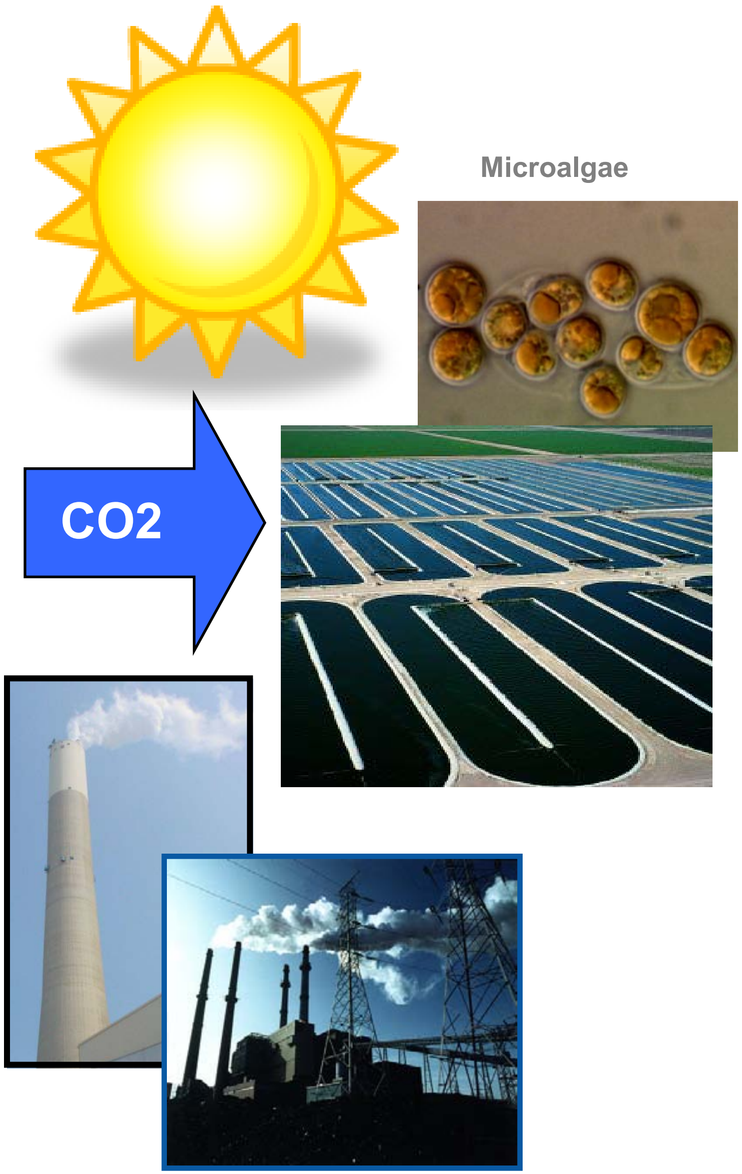
Routes to Algal Fuels



What Are the Requirements?

Production of algal oil requires:

- Land
- Sunlight
- Water
- CO_2
- Macro- and micronutrients

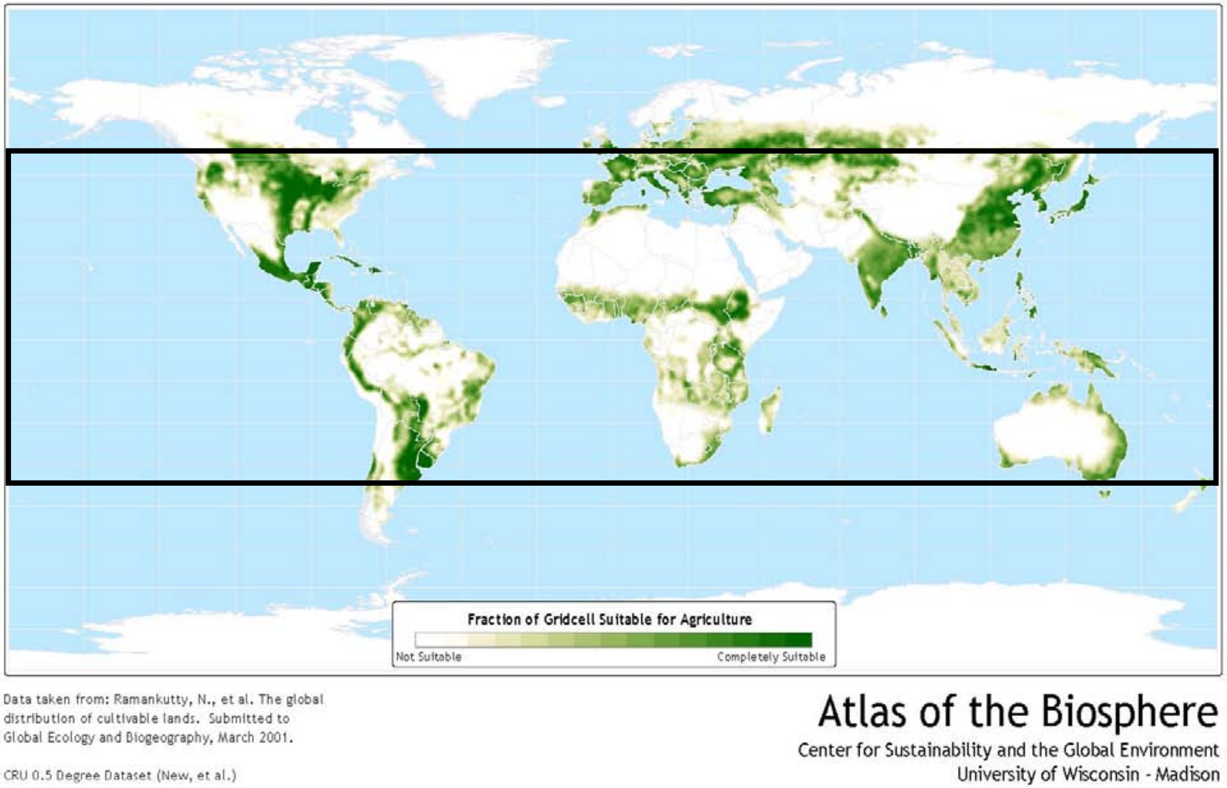


Resource Requirements

	Soybean	Algae*
gal/year	3 billion	3 billion
gal/acre	48	1200
Total acres	62.5 million	2.5 million
Water usage		6 trillion gal/yr
CO_2 fixed		70 million tons/yr
Price per gallon	$4.80	~$6

* For algae grown in open ponds with productivity of 10 g/M^2/day with 15% TAG.

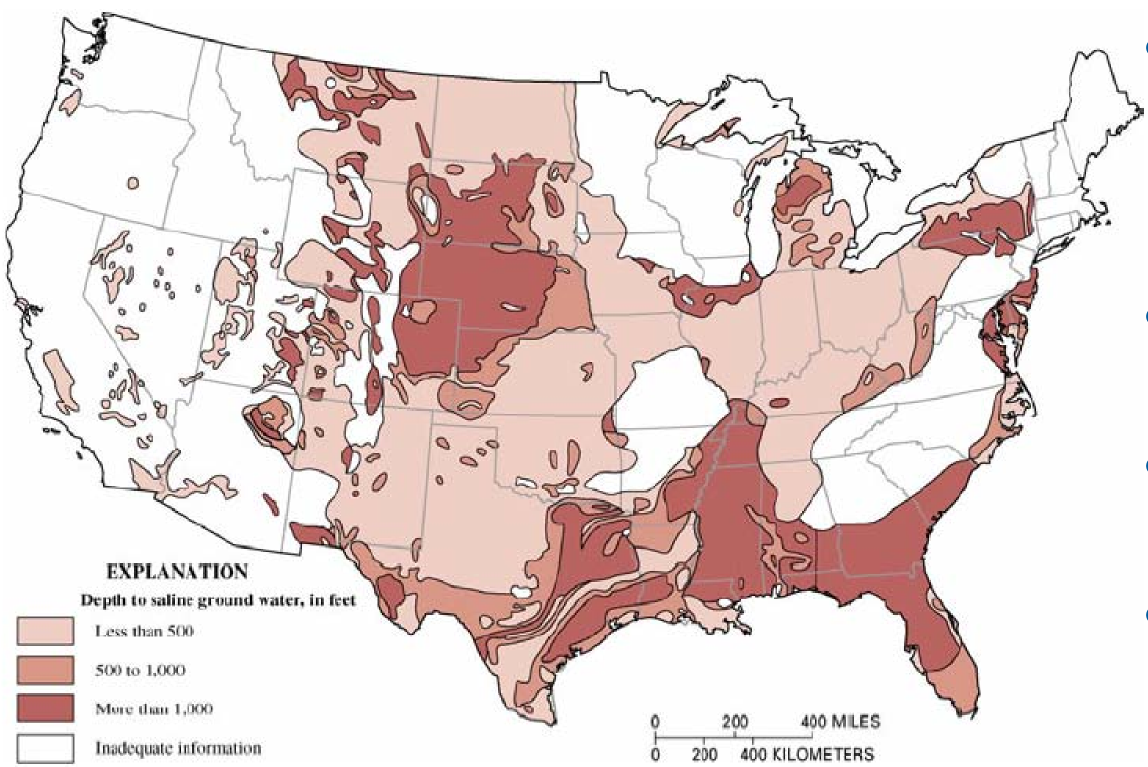
Vast Areas of the Globe Are Not Suitable for High Levels of Terrestrial Agriculture



But could be used for algal culture.

Resource Requirement: Water

Saline aquifers in the U.S.



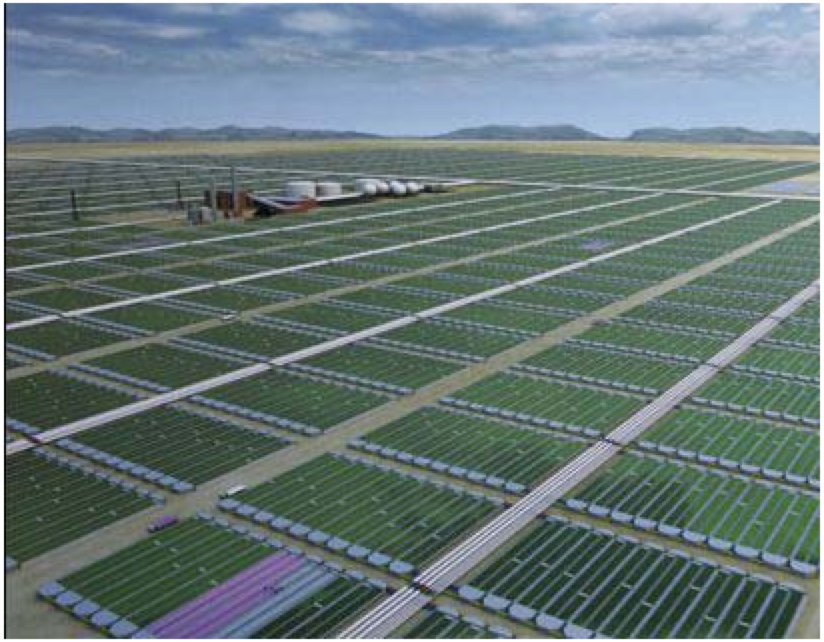
Feth and others, 1965

- Water with few competing uses
- Water resources show many areas of intersection with cheap land and CO2 sources
- "Produced water" from oil wells potential source
- Seawater available in many parts of the world
- Identify ideal sites with more recent information

USGS

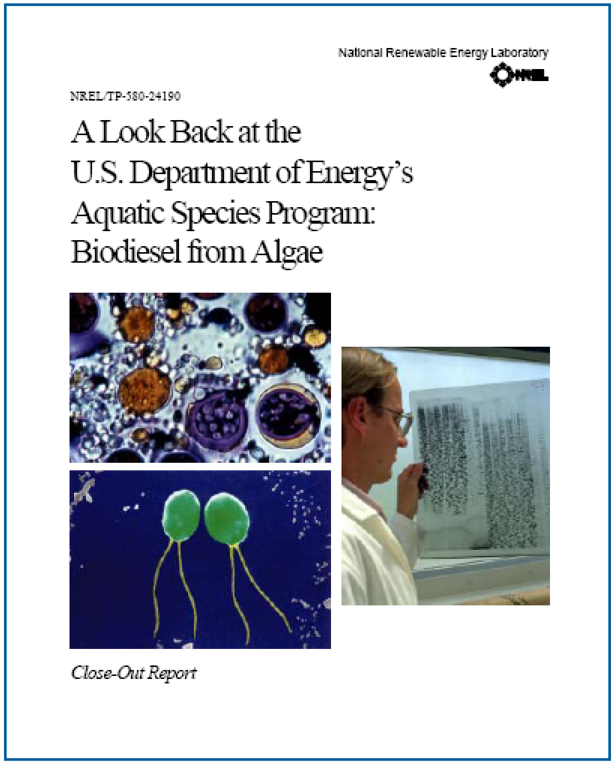
Huge Potential for Algal Biofuels

- Scenarios for producing substantial amount of diesel from microalgae are not unrealistic
- A major dedicated effort is necessary
- Significant R&D is required to optimize yields in order to realize realistic scenarios of land and water use



NREL's Aquatic Species Program

- Research project at NREL from 1978 to 1996
- 3,000 strains of algae collected and screened;
- Advances in applied biology and design of algae production systems achieved
- 1000m^2 open pond facility operated in Roswell, New Mexico for one year
- Final cost estimates for algal lipids \$40 - \$70 per bbl oil (Benemann and Oswald, 1996)
- Program cancelled in face of declining budget to focus on cellulosic ethanol
- Final report remains an important resource for algae researchers worldwide



http://govdocs.aquake.org/cgi/reprint/2004/915/9150010.pdf

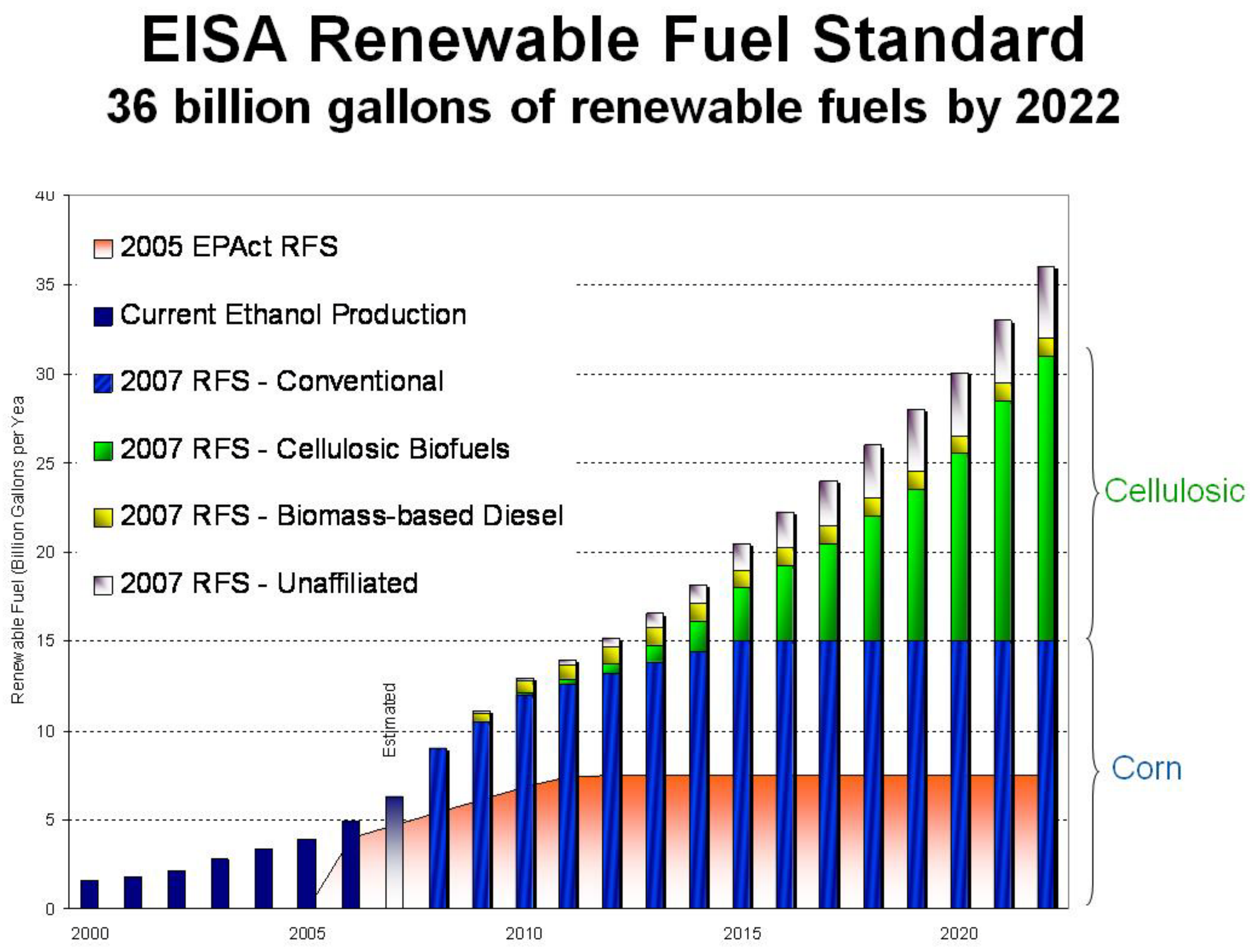
Technology Future – What's Changed Since 1996?

- Oil prices, at record highs last year, are expected to rise again
- Increased interest in CO_2 capture, carbon trading, etc.
- Greater emphasis on energy security
- New photobioreactor designs, advances in material science
- Explosion in biotechnology
  - Advances in metabolic engineering
  - Genomics, proteomics, metabolomics, bioinformatics, etc.

2007 Energy Independence and Security Act (EISA)

- Increase the availability of renewable energy that decrease GHG emissions
- Increase the Renewable Fuel Standard to 36 billion gallons by 2022.
- Secretary of Energy to present a report to Congress on the feasibility of microalgae as a feedstock for biofuels production
  - Identify continuing research and development challenges
  - Identify regulatory or other barriers
  - Make recommendations for development as a viable transportation fuel.

2007 RFS Does Not Mention Algae

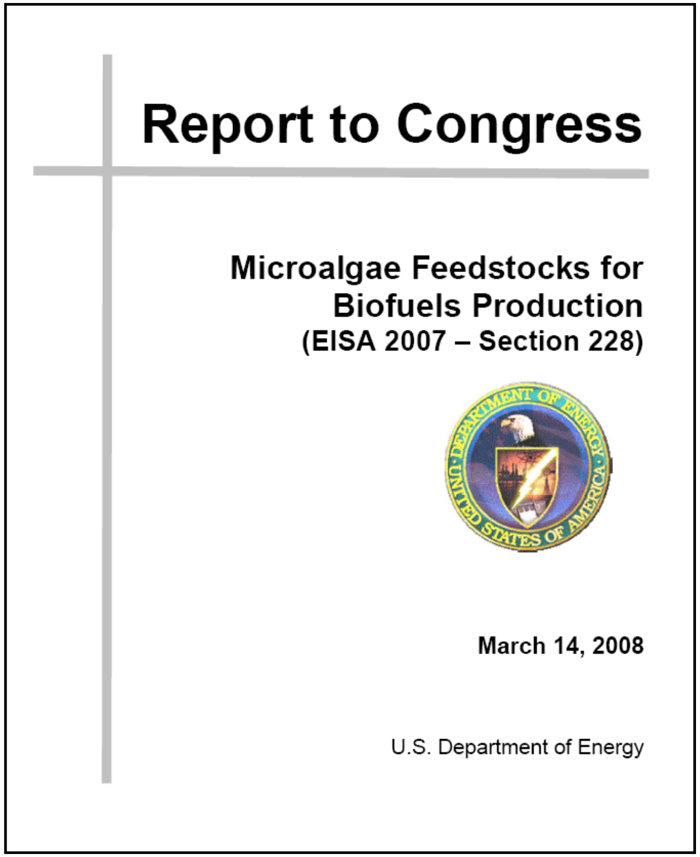


Source: EISA 2007, Sec. 202, p. 121 Stat 1522-1523

National Renewable Energy Laboratory
Innovation for Our Energy Future

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

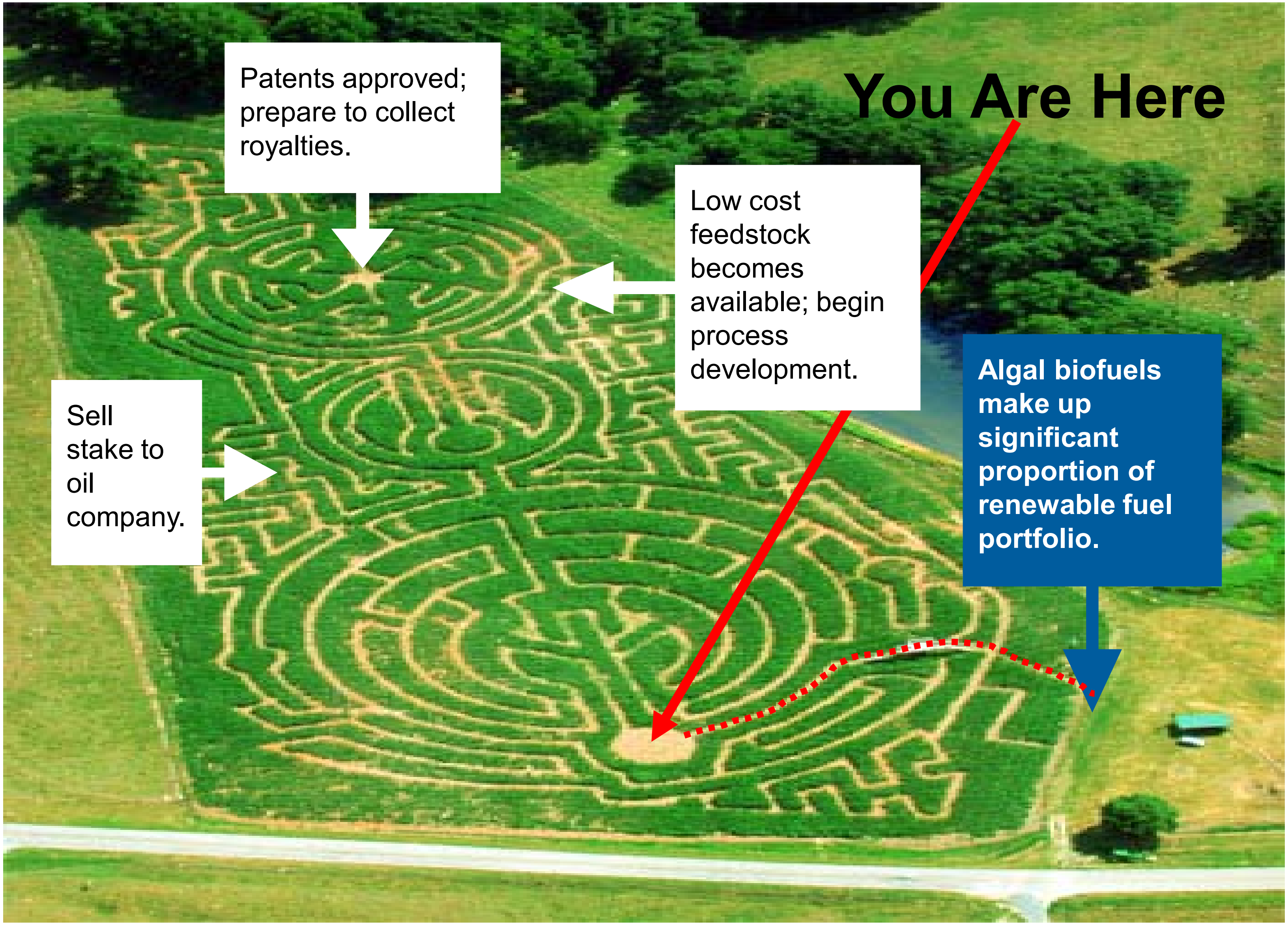
Algal Biofuels Technology Roadmap Workshop

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

December 9-10, 2008
University of Maryland, Inn and Conference Center

- Drew upon the expertise of a carefully balanced group of scientists and other experts in the various required disciplines
- Input to help define activities needed to resolve uncertainties associated with commercial scale algal biofuel production
- Workshop planned and executed by DOE, NREL, SNL, and ORISE
- Workshop venue: University of Maryland Inn and Conference Center Dec 9-10; initial roadmap writing session Dec 11-12
- Workshop included plenary presentations and breakout sessions covering technical, industrial, resource, and regulatory aspects of algal biofuel production
- First draft of Roadmap complete; editing in progress

Different Definitions of Success

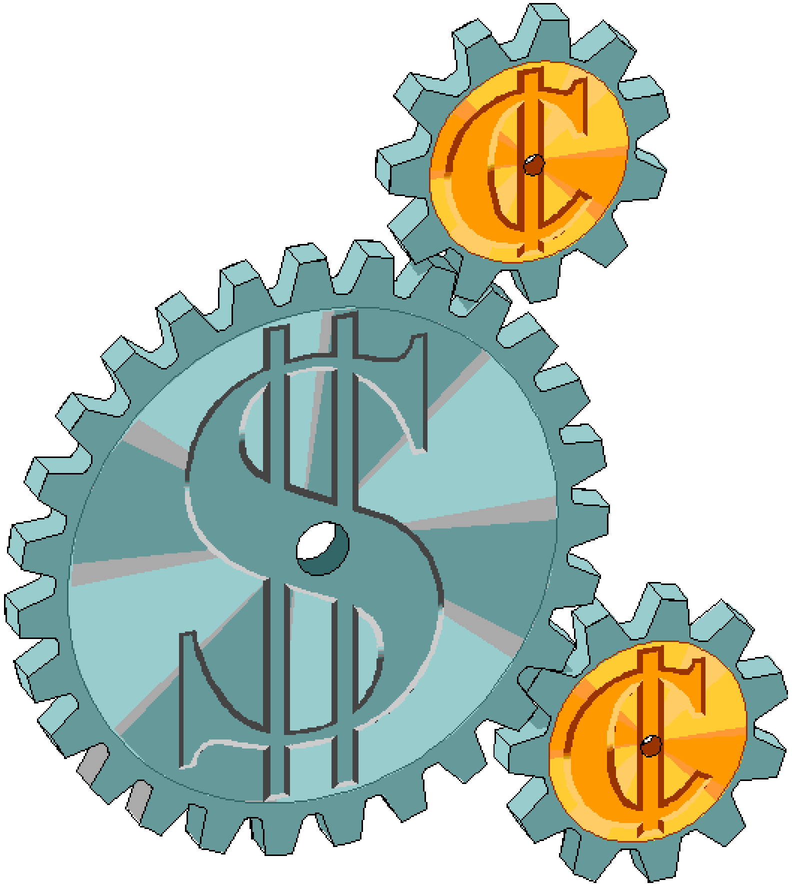


Roadmap Outline

- Executive Summary
- Introduction .
- Leadership & Collaboration to Achieve the Vision
- Standards, Regulation and Policy
- Partnerships
- Systems & Technoeconomic Analysis of Algal Biofuels Prospects
- Science, Engineering and Scale-Up Strategy
  - Feedstock
  - Processing and Conversion
  - Closing the Fuel Cycle – Starting with the End in Mind
- Summary and Conclusions

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

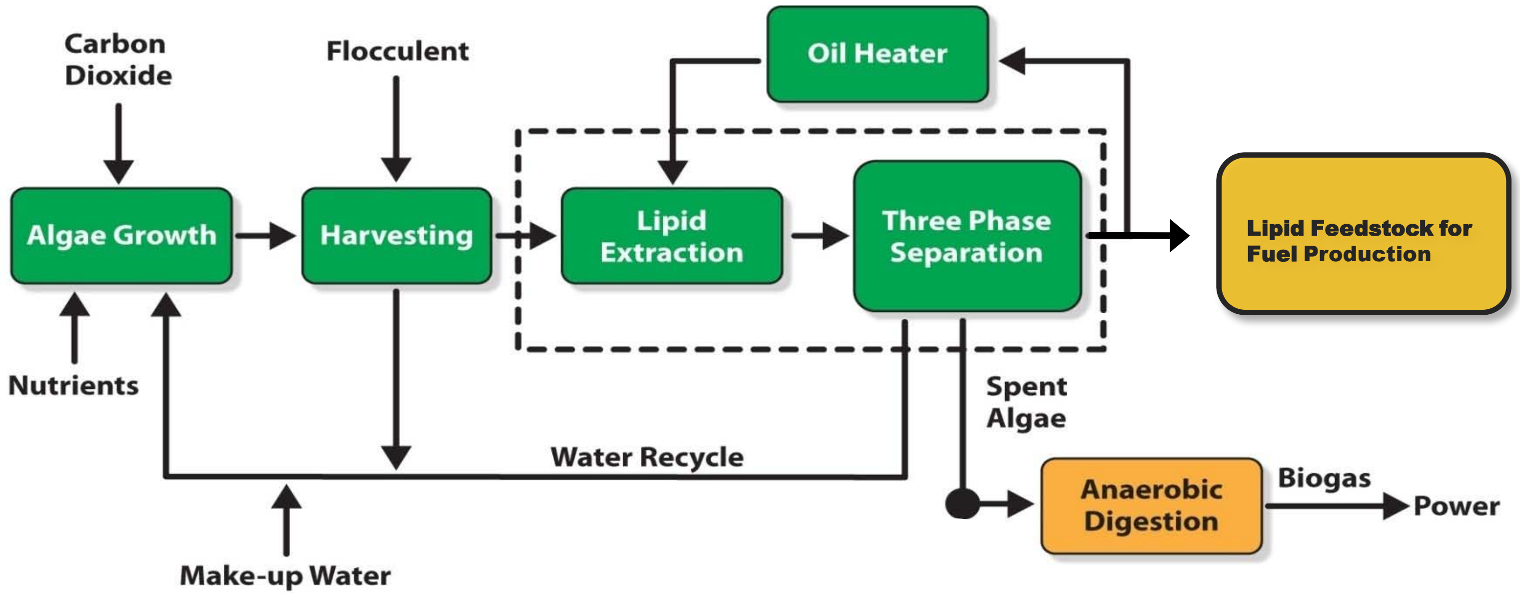


A Lesson in Economics

Annual income twenty pounds, annual expenditure nineteen pounds nineteen and six, result happiness. Annual income twenty pounds, annual expenditure twenty pounds ought and six, result misery

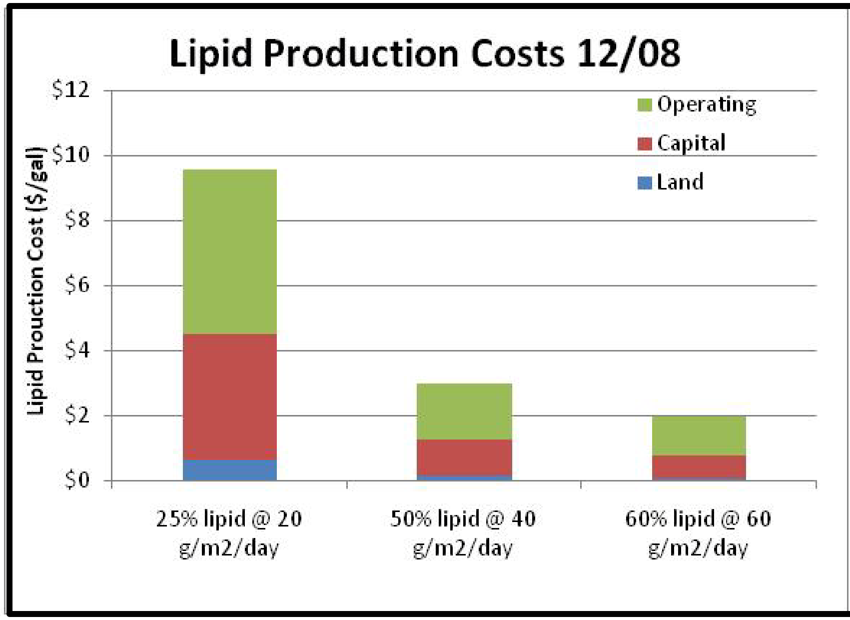
But, are there no carbon credits? Are there no government subsidies?

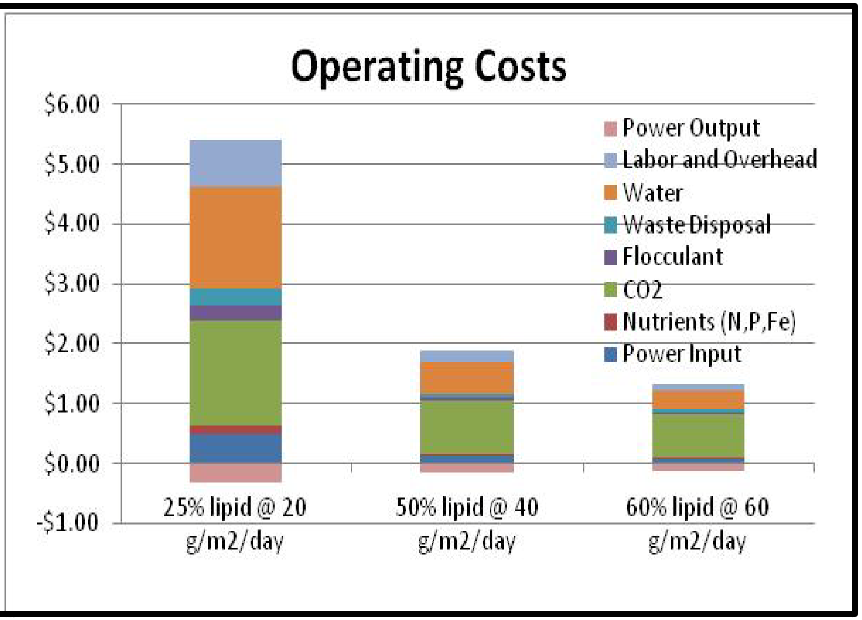
NREL Process Design for Technoeconomic Modeling



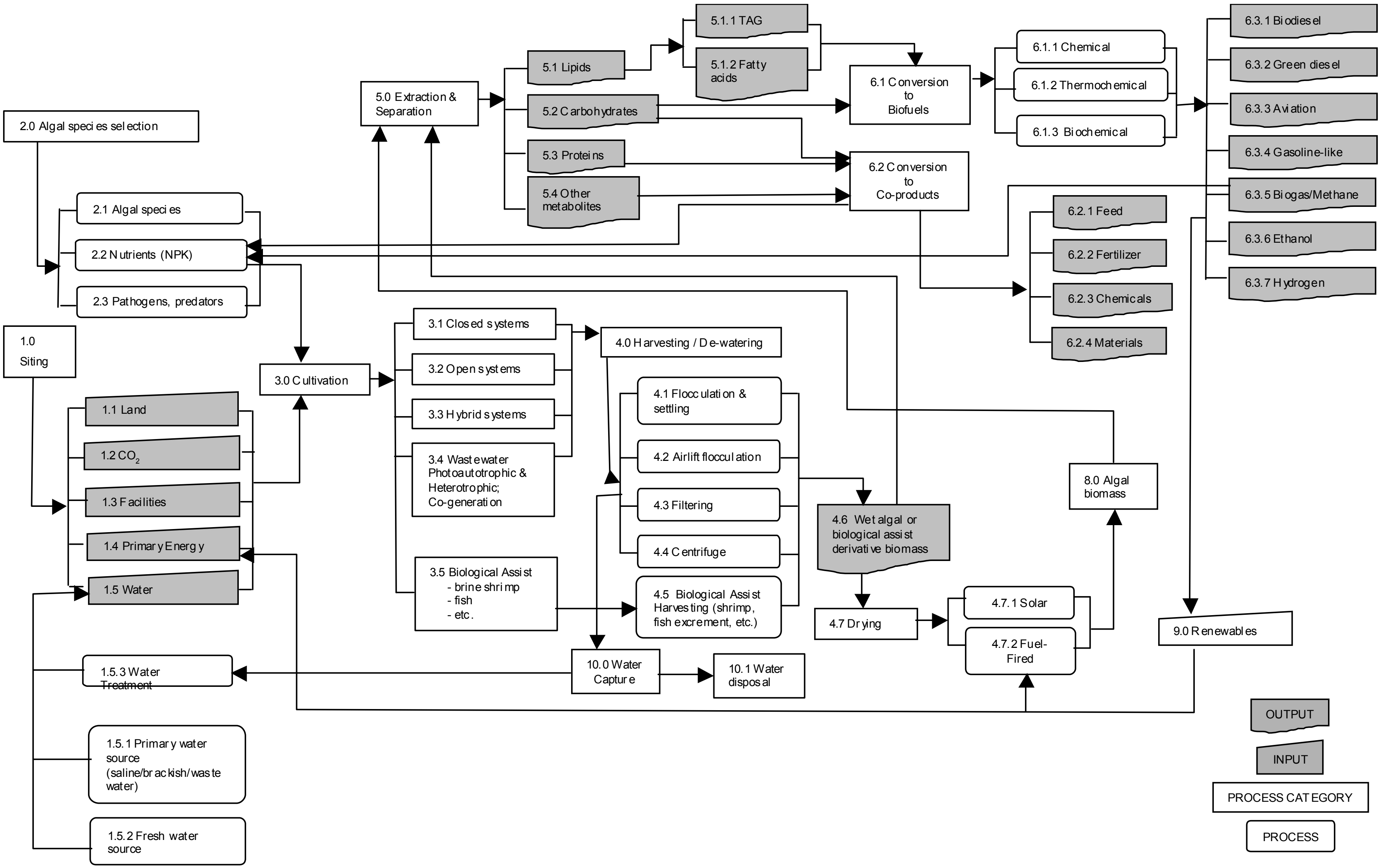
Based on: Benemann J.R. and W.J. Oswald. Final Report to US DOE NETL, 1996
"Systems and economic analysis of microalgae ponds for conversion of CO_2 to biomass"
http://www.osti.gov/bridge/servlets/purl/493389-FXQyZ2/webviewable/493389.pdf

Increasing Biological Productivity Key to Reduced Costs





It's Not So Simple



Technoeconomic Modeling for Workshop

NREL
- Al Darzins
- David Humbird
- Phil Pienkos

NMSU
- Pete Lammers
- Meghan Starbuck

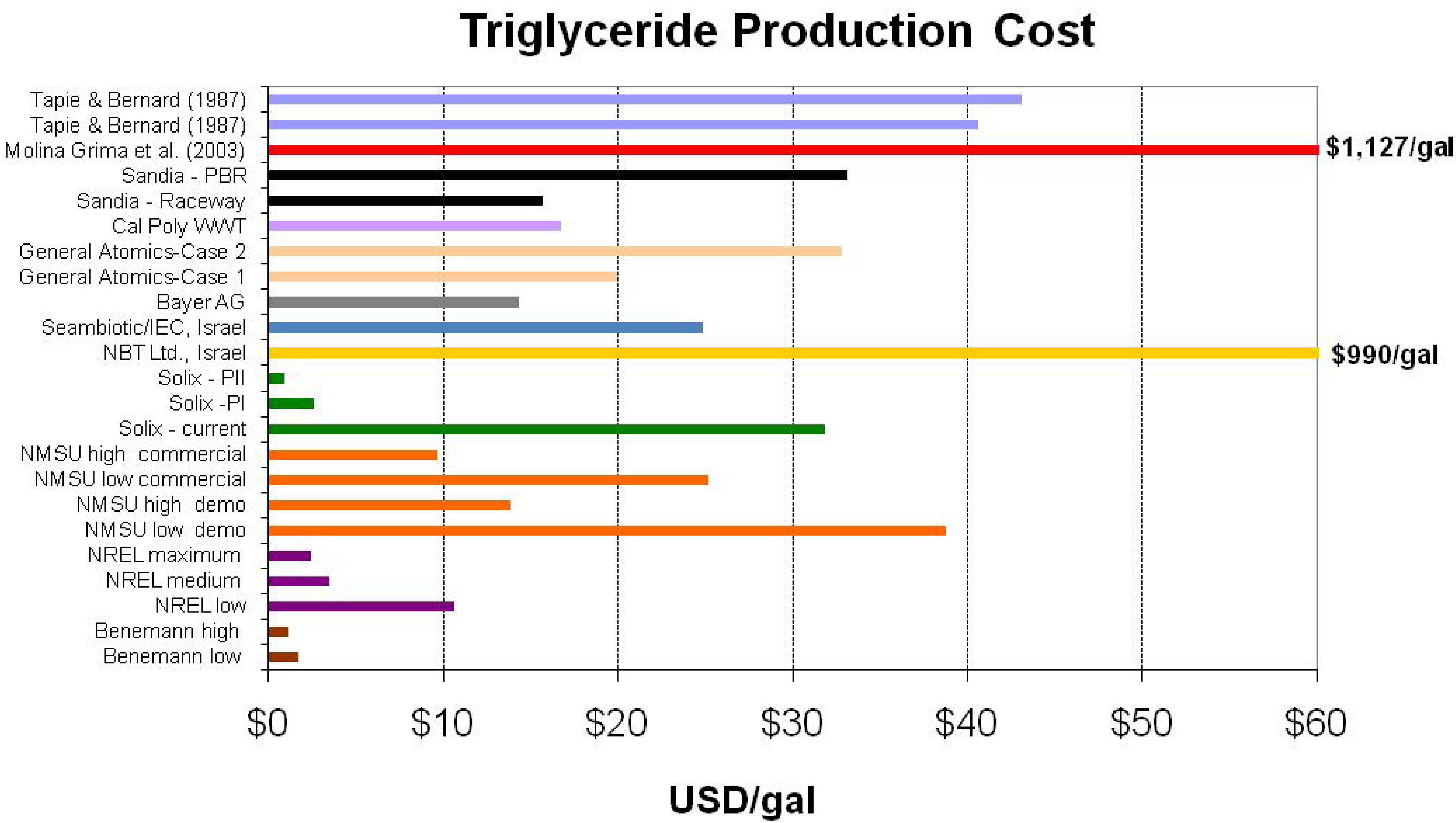
CSU
- Bryan Willson

SNL
- Katherine Dunphy-Guzman
- Ray Finley
- Geoff Klise
- Len Malczynski
- Ron Pate
- Amy Sun
- Cecelia Williams

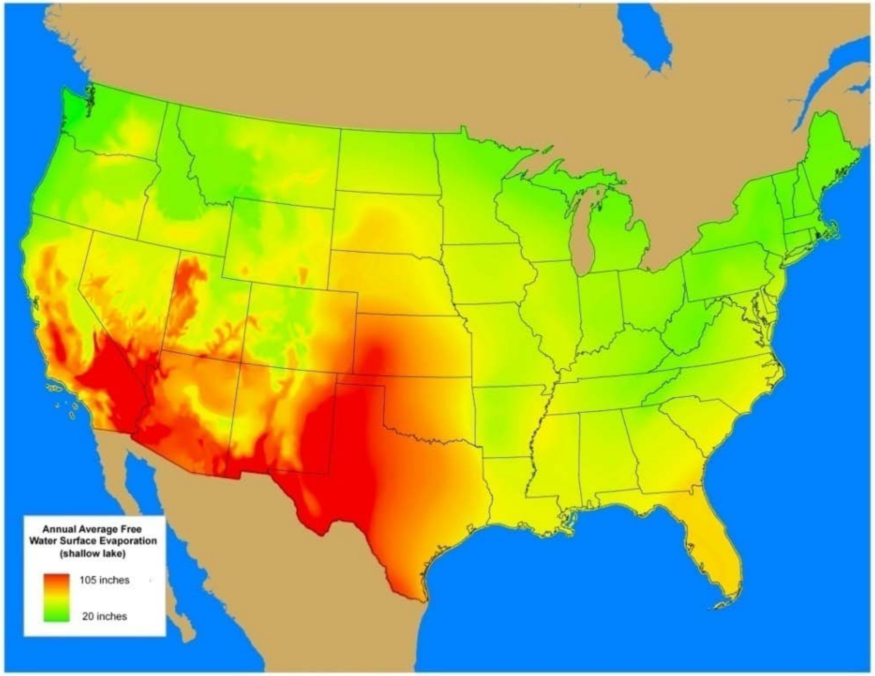
Sources for Economic Data

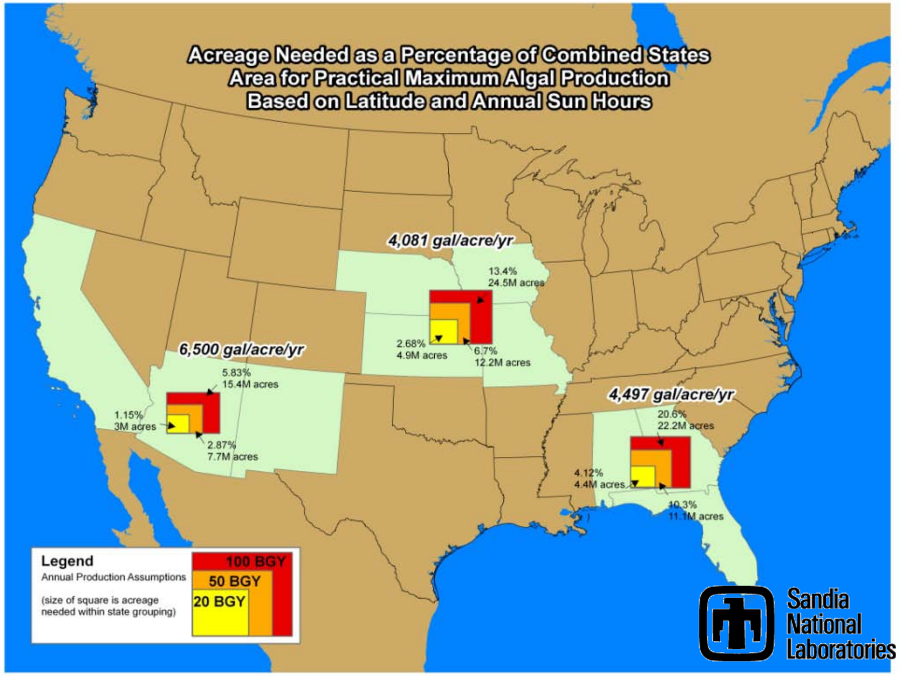
Source	Authors	Year	Reference
NREL	Matt Ringer Bob Wallace Phil Pienkos	2008	Analysis completed for this exercise
NMSU	Meghan Starbuck Pete Lammers	2008	Analysis completed for this exercise
Solix	Bryan Willson	2008	2nd Bundes-Algen-Stammtisch
Seambiotics	Ami Ben-Amotz, Israel	2007-2008	Algae Biomass Summit
Sandia	Ben Wu	2007	Analysis completed for this exercise
Bayer	Ulrich Steiner	2008	European White Biotechnology Summit
General Atomics	David Hazlebeck	2008	Algae Biomass Summit
California Polytechnic Institute	Tryg Lundquist	2008	Algae Biomass Summit
University of Almeria	E. Molina Grima E. Belarbi F. Fernandez A. Medina Y. Chisti	2003	Biotechnol. Adv. (2003) 20:491-515
Association pour la Recherche en Bioenergie	P. Tapie A. Bernard	1988	Biotech. Bioeng. (1988) 32:873-885
University of California	John Benemann William Oswald	1996	PETC Final Report

Summary of Algal Lipid Production Cost Estimates



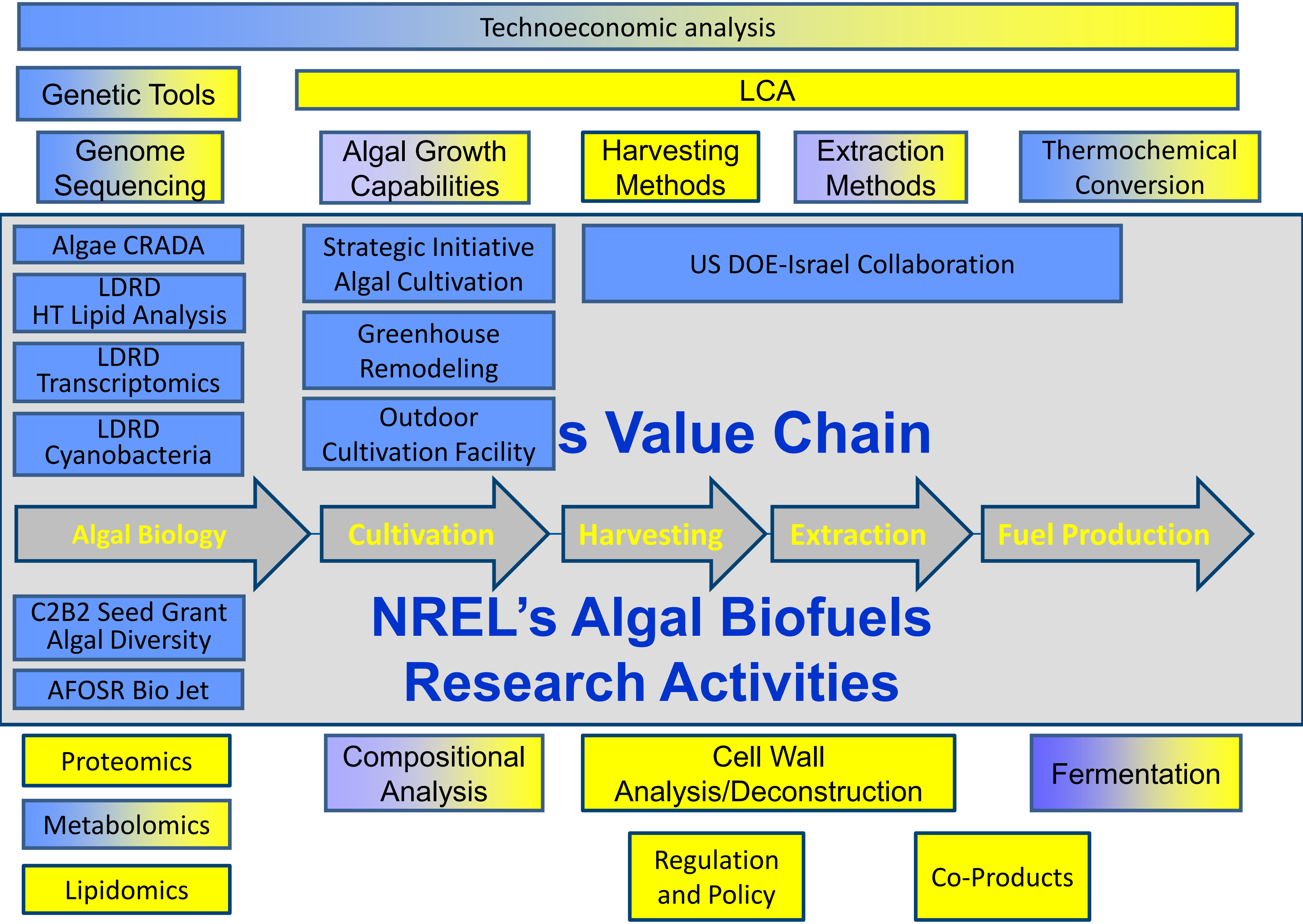
GIS Analysis Identifies Economic Sensitivities & Resource Consequences





Algal Biofuels at NREL:
Beyond the Aquatic Species Program

Process Value Chain


Technoeconomic analysis
Genetic Tools
LCA
Genome Sequencing
Algal Growth Capabilities
Harvesting Methods
Extraction Methods
Thermochemical Conversion
Algae CRADA
Strategic Initiative Algal Cultivation
US DOE-Israel Collaboration
LDRD HT Lipid Analysis
Greenhouse Remodeling
LDRD Transcriptomics
LDRD Cyanobacteria
Outdoor Cultivation Facility
s Value Chain
Algal Biology
Cultivation
Harvesting
Extraction
Fuel Production
C2B2 Seed Grant Algal Diversity
AFOSR Bio Jet
NREL's Algal Biofuels
Research Activities
Proteomics
Compositional Analysis
Cell Wall Analysis/Deconstruction
Fermentation
Metabolomics
Lipidomics
Regulation and Policy
Co-Products

NREL Support to USAF

Air Force Office of Scientific Research (AFOSR) Collaboration

2007-2008

- Algal biofuels research program
- NREL-AFOSR algae workshop
  Feb 19-21, 2008 (Arlington, VA)

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

2009-2011

- Continuing NREL-AFOSR collaboration: Biohydrogen/Bio-jet fuels
- NREL being integrated into AFOSR Bio-jet research program

Chevron Algae CRADA

2nd Collaborative Research and Development Agreement (CRADA) under Chevron/NREL Alliance

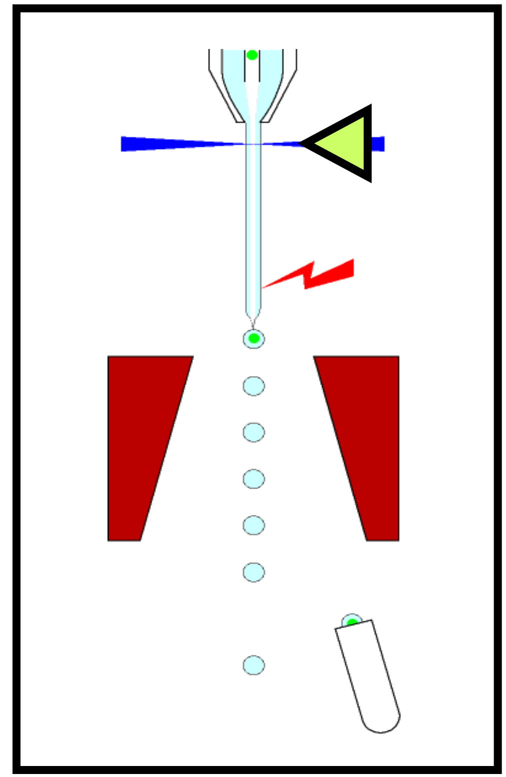
Goal: Identify and develop algae strains that can be economically harvested and processed into finished transportation fuels

Strategic Equipment Acquisitions

NREL General Purpose Equipment (GPE)

Fluorescence Activated Cell Sorter (FACS)

Custom BD FACS*Aria*



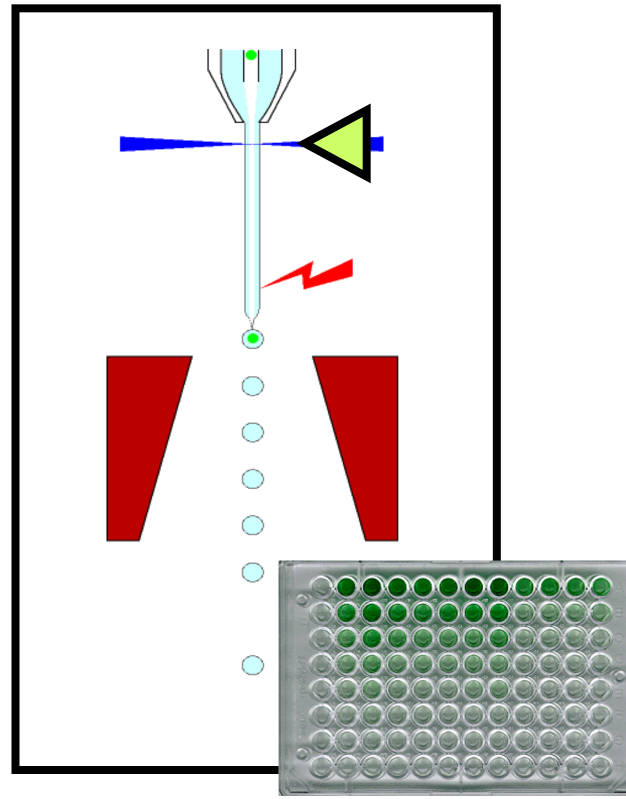
Capability: High-speed algal cell sorting (populations and individual cells)

Strategic Equipment Acquisitions

NREL General Purpose Equipment (GPE)

Fluorescence Activated Cell Sorter (FACS)

Custom BD FACS*Aria*

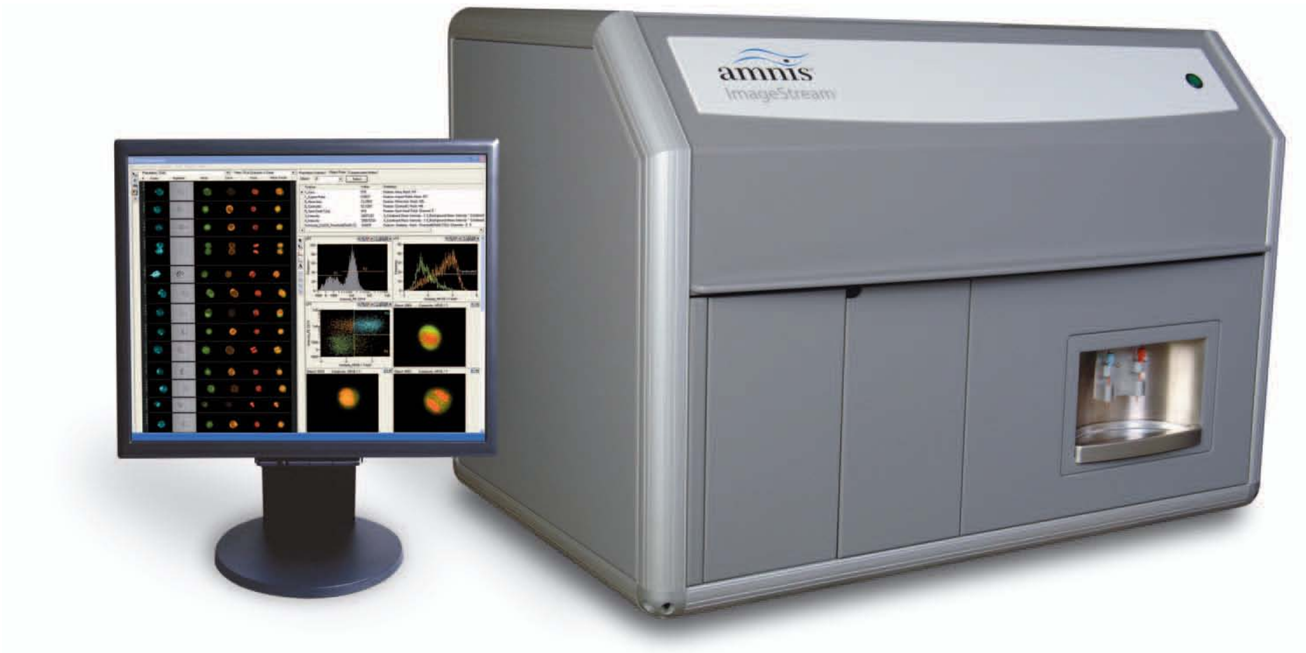


Capability: High-speed algal cell sorting (populations and individual cells)

Strategic Equipment Acquisitions

NREL General Purpose Equipment (GPE)

Imaging Flow Cytometer (Amnis - Imagestream®)



- Combines quantitative cellular imagery with powerful population statistics
- Performs darkfield, brightfield, and fluorescence (3 lasers) imaging
- Captures 10,000 cell images per minute

Strategic Equipment Acquisitions

Establishment of a Cryopreservation System for Long-Term Maintenance of Algal Cultures

- Minimize damage during low temperature freezing and storage
- Maintain long-term cell viability – preserve intellectual property

Images courtesy: Eric Knoshaug, NREL

Strategic Facilities Investment

NREL General Plant Projects (GPP)

FTLB Greenhouse Renovation

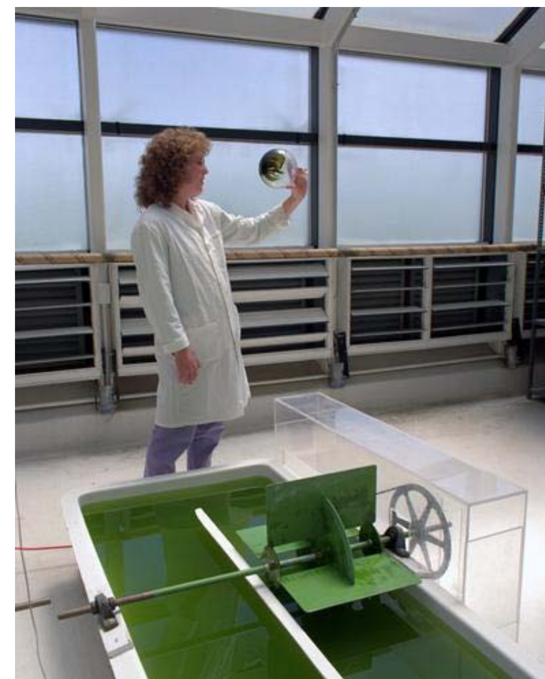
Construction of a new 500 sq ft algal lab

Strategic Facilities Investment

NREL General Plant Projects (GPP)

FTLB Greenhouse Renovation

Construction of a new 500 sq ft algal lab



Facilities: Large-scale algae cultivation

NREL's South Table Mountain
(2-5 kg/day)

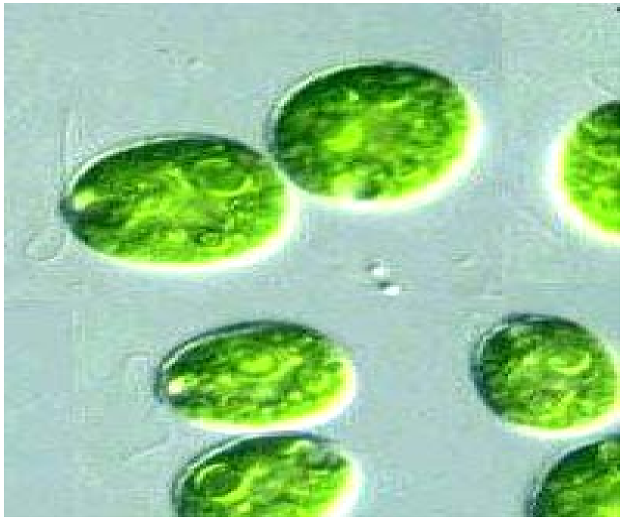
Warren Tech H.S.
(10,000 sq. ft greenhouse)

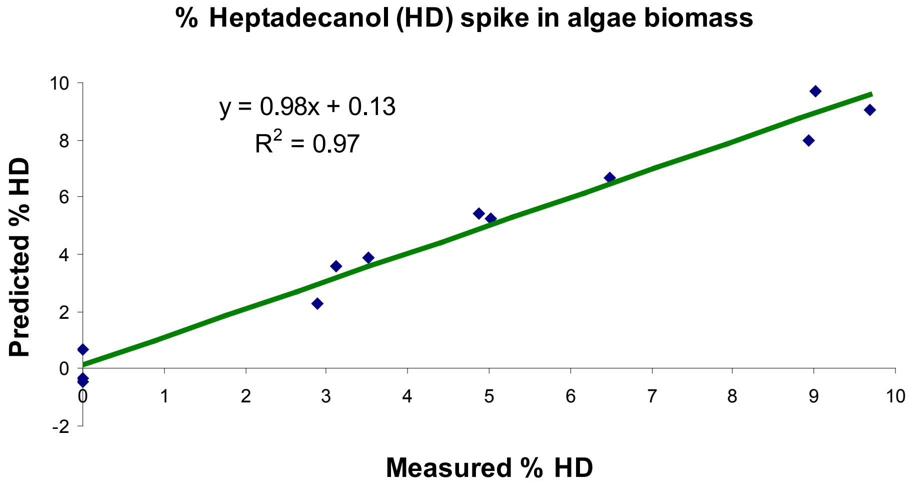
NREL LDRD Project #1

Laboratory Directed Research & Development (LDRD) Award - 2008

"Development of a Comprehensive High-Throughput Technique for Assessing Lipid Production in Algae"

P.I.: E. Wolfrum, co-PI: A. Darzins; post-doc, L. Laurens



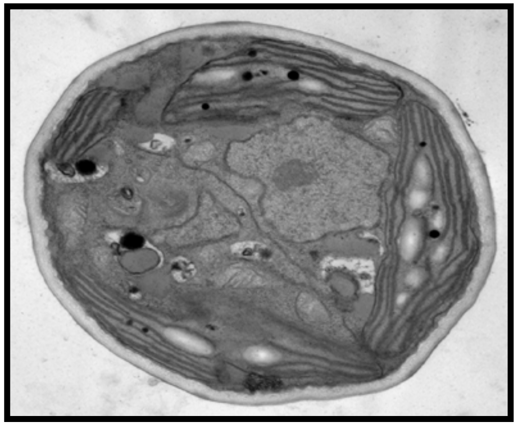


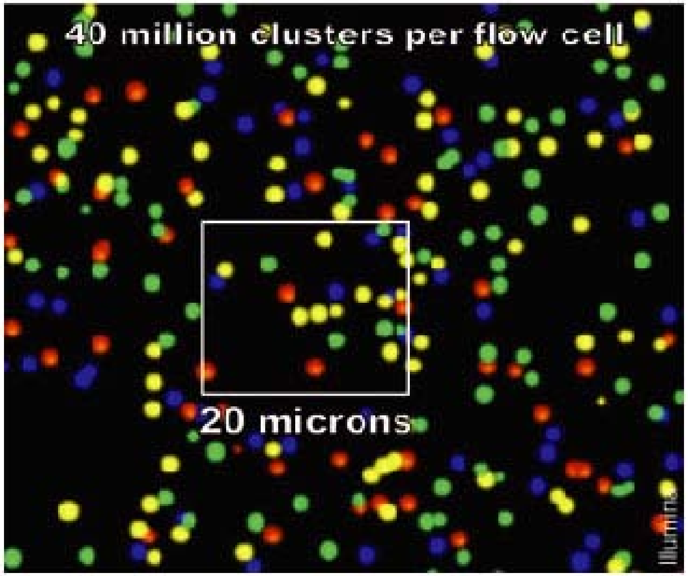
NREL LDRD Project #2

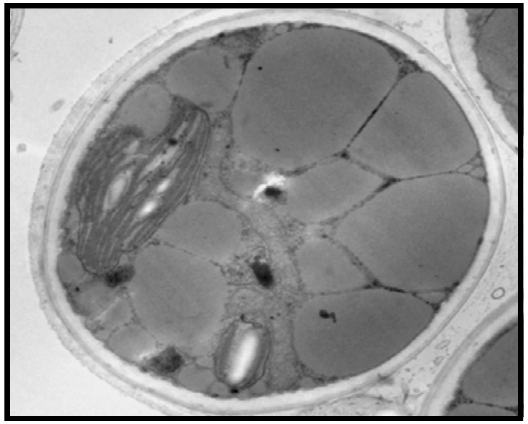
Laboratory Directed Research & Development (LDRD) Award

"Use of Digital Gene Expression (DGE): Tag Profiling for High Throughput Transcriptomics in Microbial Strains Involved in Advanced Biofuel Production"

P.I., P. Pienkos; co-PIs, M. Ghirardi and A. Darzins







Photos courtesy: Q. Hu, ASU

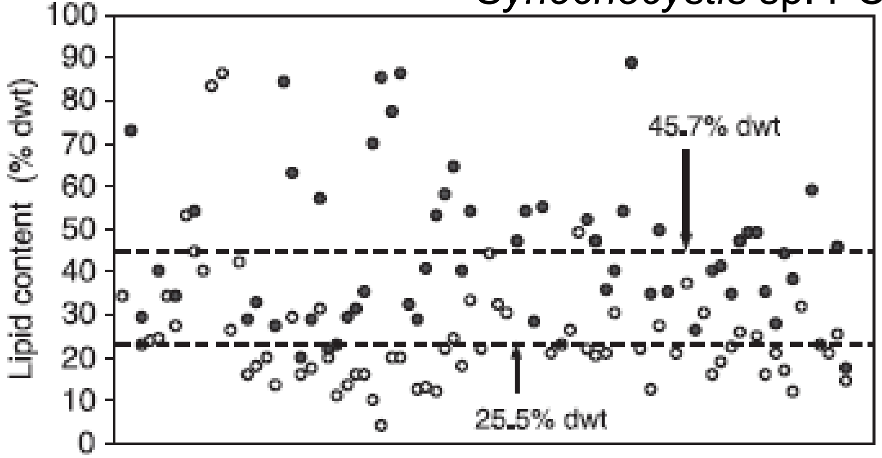
NREL LDRD Project #3

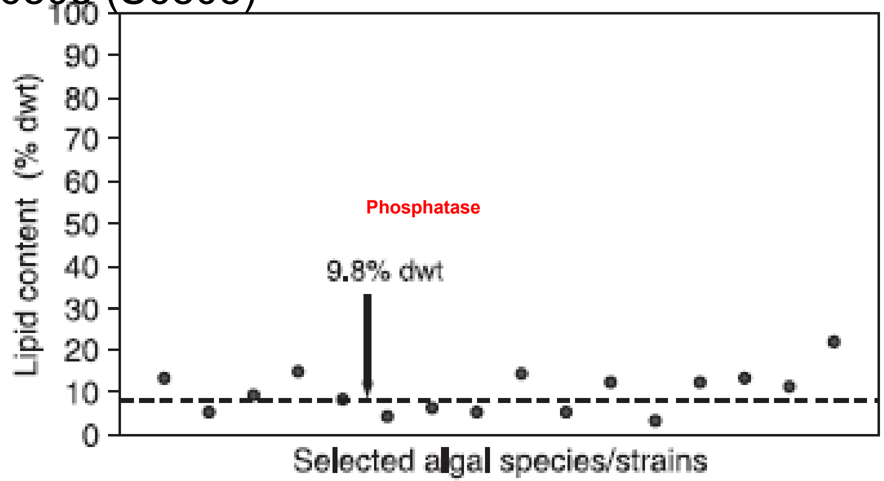
Laboratory Directed Research & Development (LDRD) Award

“Biodiesel from *Cyanobacteria*”

P.I., J. Yu; co-PIs, P. Maness, P. Pienkos and A. Darzins

Synechocystis sp. PCC6803 (S6803)





Hu, Q., Sommerfeld, M., Jarvis, E., Ghirardi, M., Posewitz, M., Seibert, M. and Darzins, A. (2008) Microalgal triacylglycerols as feedstocks for biofuel production: perspectives and advances. The Plant Journal 54:621-639.

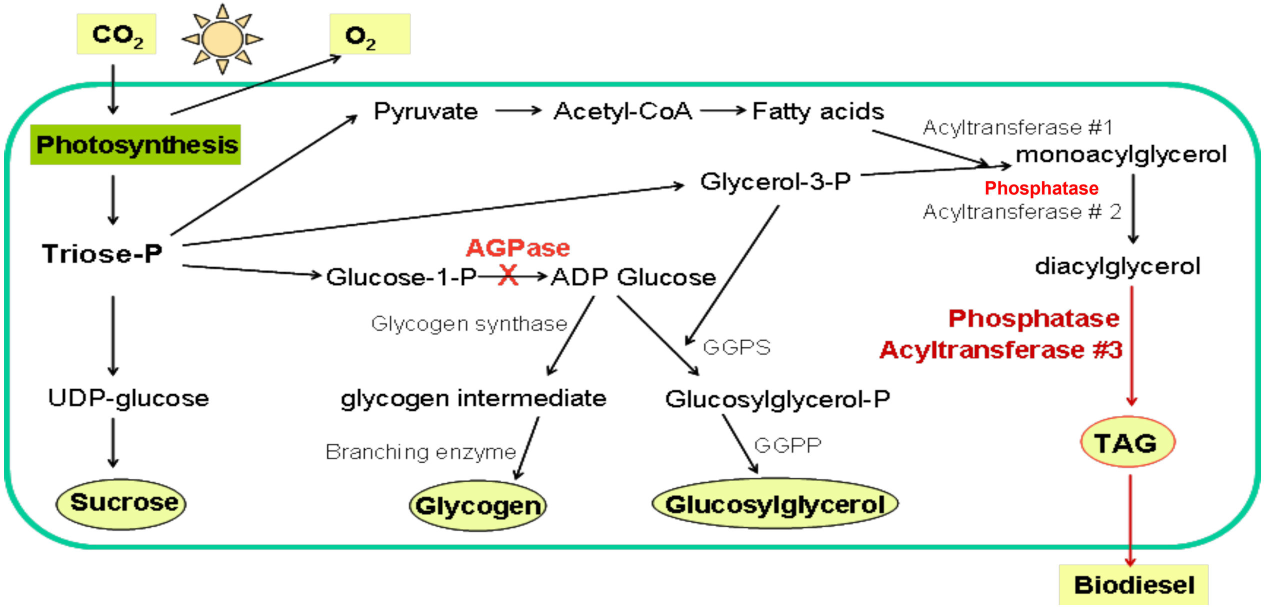
NREL LDRD Project #3

Laboratory Directed Research & Development (LDRD) Award

"Biodiesel from *Cyanobacteria*"

P.I., J. Yu; co-PIs, P. Maness, P. Pienkos and A. Darzins

Synechocystis sp. PCC6803 (S6803)



C2B2 Seed Grant Project

Colorado Center for Biorefining and Biofuels (C2B2) 2007/2008 Seed Grant Award

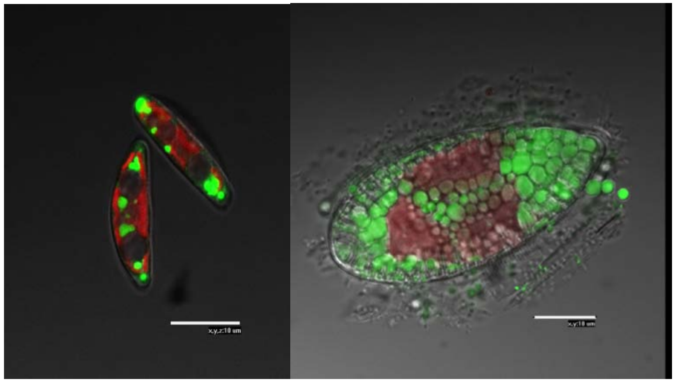
“Establishment of a Bioenergy-Focused Microalgae Strain Collection Using Rapid, High-Throughput Methodologies”

P.I., A. Darzins; co-PI, M. Posewitz; L. Elliott; R. Sestric

National Renewable Energy Laboratory (NREL) and Colorado School of Mines

C2B2
Profit From Our Synergy
Colorado Center for Biorefining and Biofuels

University of Colorado
Colorado State University
Colorado School of Mines
National Renewable Energy Laboratory



http://www.c2b2web.org

DOE-Israel Collaboration

Development of Novel Microalgal Production and Downstream Processing Technologies for Alternative Biofuels Applications

Joint NREL/SNL/Private Industry Collaboration

Goals:

- Engineering processes for producing/harvesting algal biomass.
- Develop methods of extracting oil from algal biomass
- Use algal biomass/residues as a gasification and pyrolysis feedstock
- Life Cycle Analysis (LCA)

Seambiotic

Image courtesy: A. Ben-Amotz, Seambiotic

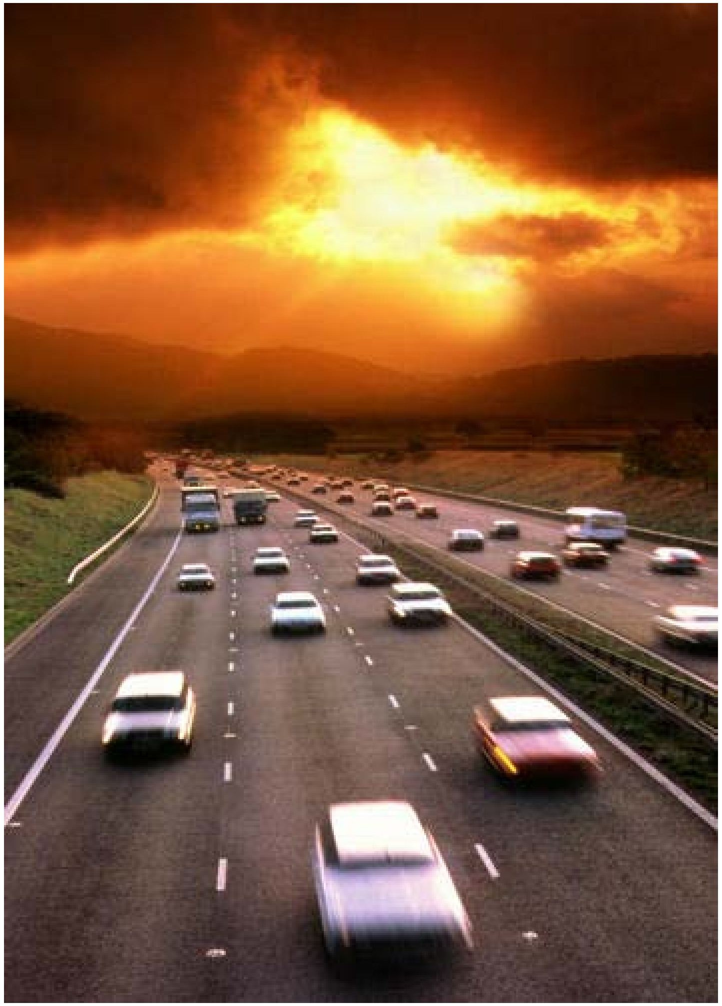
Ashkelon, Israel

Conclusions

- Low petroleum costs and high predicted costs for algal lipid production prompted the DOE to close the ASP in 1996.
- In 2006, NREL began to re-evaluate the potential for algal biofuels and initiated a program to revive the ASP.
  - This work led to a number of mechanisms of support for algal research at NREL
    - Partnerships with DOD through the Air Force Office of Scientific Research
    - Partnerships with industry though a CRADA with Chevron and DOE-Israel collaboration
    - Public-Private partnerships with industry and universities through C2B2
    - Internally funded support for infrastructure improvements and research projects involving cutting edge technologies
- DOE has come to recognize the promise of algae in its portfolio of advanced biofuels and is working to establish a roadmap to support the acceleration of algal biofuel commercialization.

Additional information available

- DOE Algae Roadmap: https://www.orau.gov/algae2008/
- Algae activities at NREL: http://www.nrel.gov/biomass/proj_microalgae.html



Closing the Fuel Cycle

- Siting and Resources
- Distribution and Utilization