National Renewable Energy Laboratory
Innovation for Our Energy Future

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

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

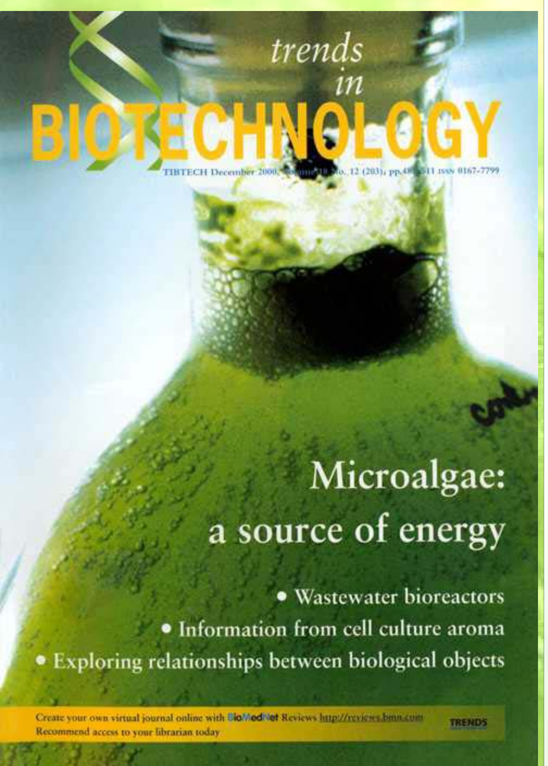
Dilemma: Biodiesel from current oilseed crops cannot come close to meeting U.S. diesel demand (44 billion gal/year)

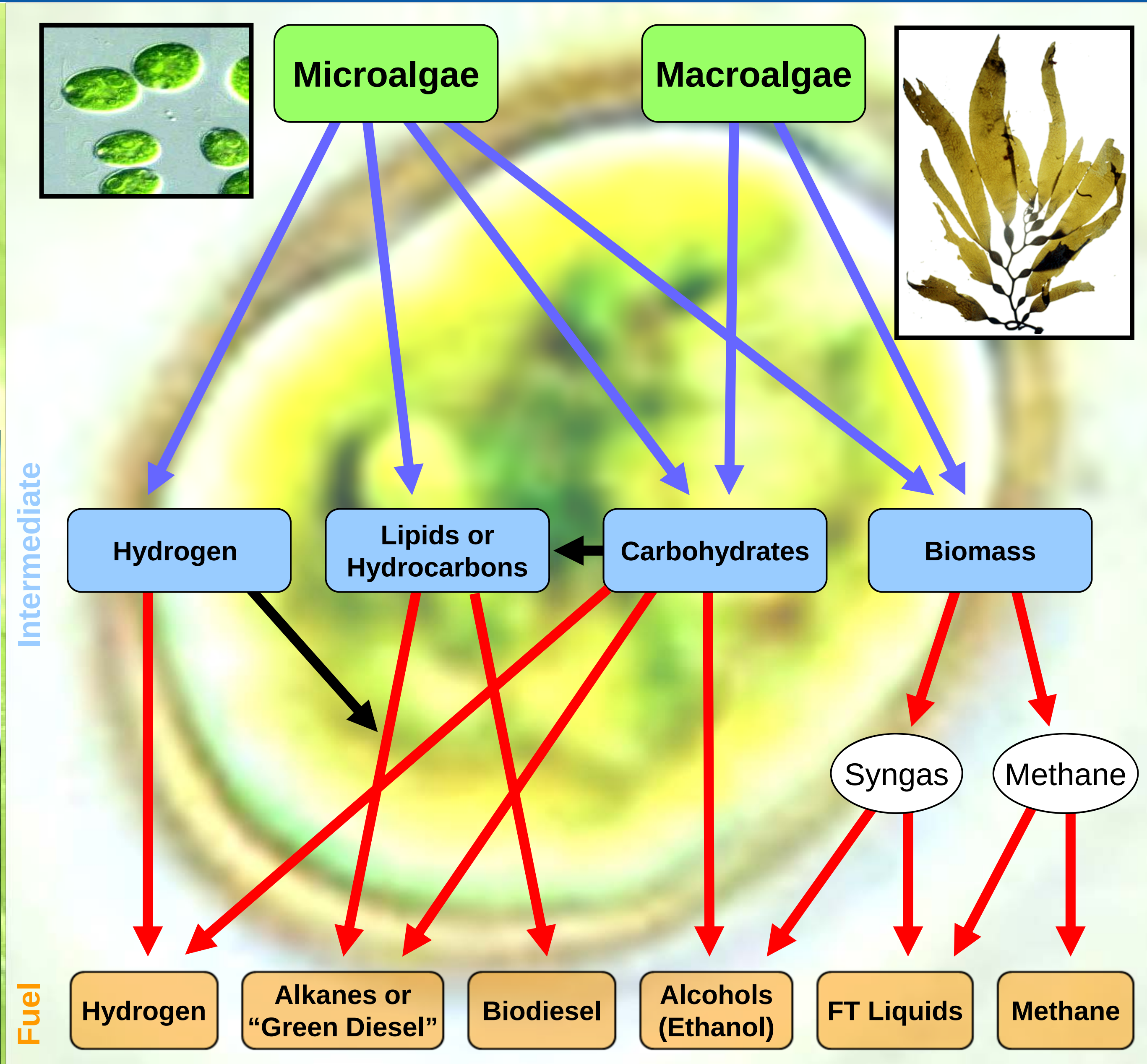
- Soy oil (2.75 B gal; 2007); replaces ~4% of U.S. demand
- Vegetable oils must compete with food market
- 2.5B gallon capacity, only 700M gallons produced in 2008

Alternative sources of oils are needed!

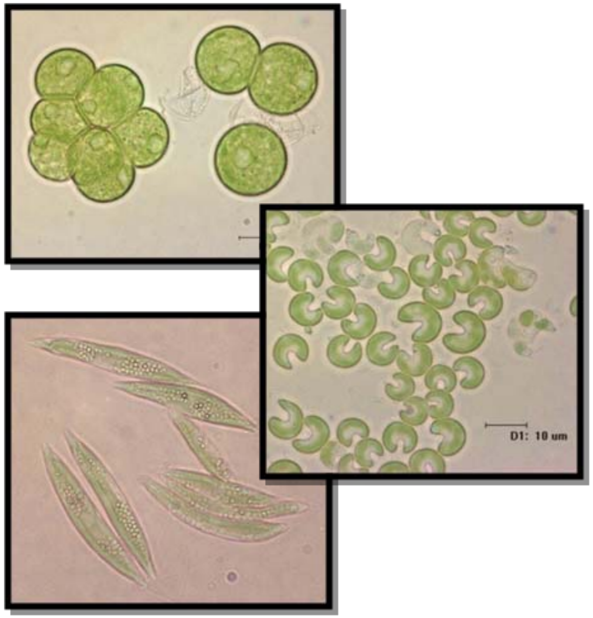
Algae: Numerous Bioenergy Routes

Defining a Biofuels Portfolio From Microalgae



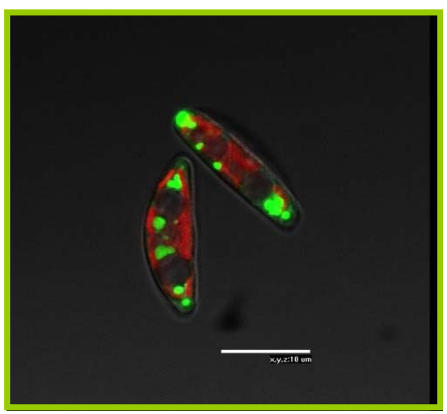


Why Fuels from Algal Oil?

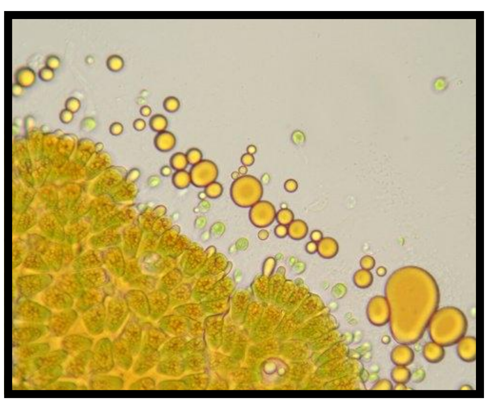


Images courtesy:
Lee Elliott, CSM

- **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 CO_2 resources (i.e., flue gas)**
- **Potential to displace significant U.S. petroleum fuel usage – requires low-cost infrastructure**



Fluorescence micrograph showing stained algal oil droplets (green)



Comparing Potential Oil 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 (20g/m^2/day-15%)	1267

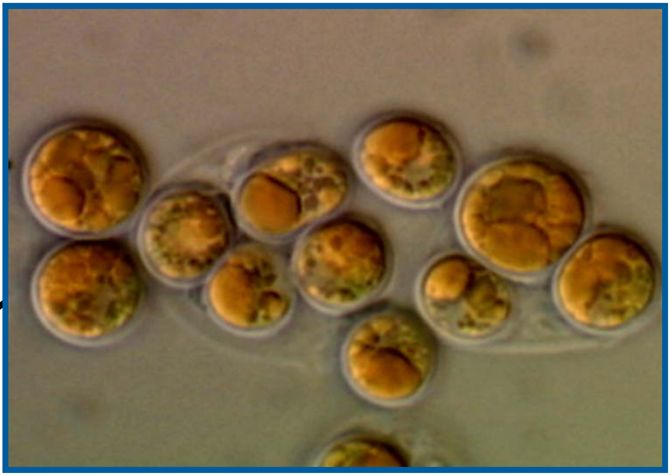
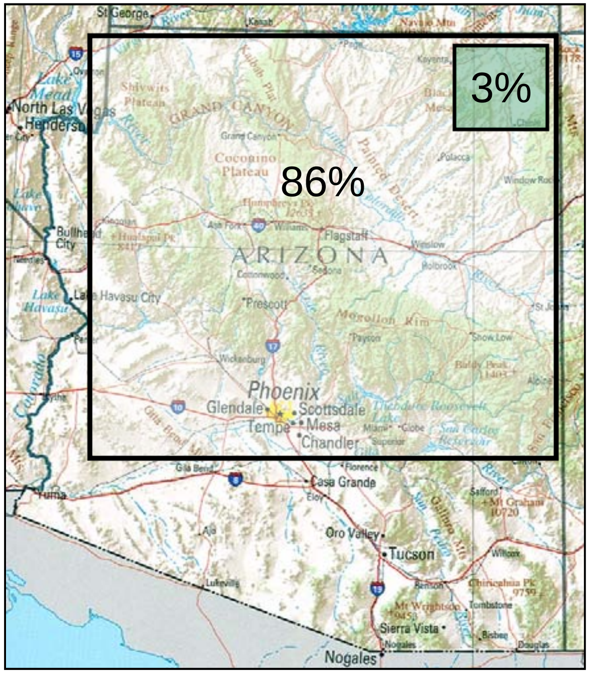


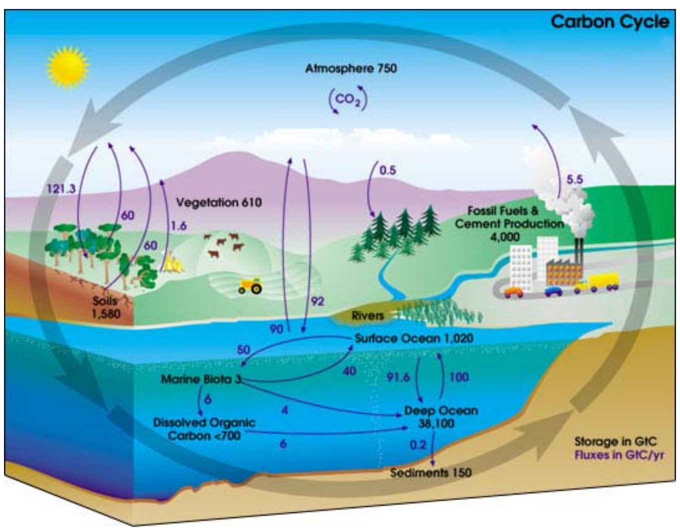
Image courtesy: Q. Hu, ASU

Algae Compared to Ethanol Crops

Biomass	Productivity	Energy (GJ/acre) 90 MJ/gallon ethanol 128 MJ/gallon oil
Sugar Cane	35 tons/acre 700 gal/acre - sugar 1440 gal/acre - bagasse	62 GJ/acre (sugar to ethanol only) 191 GJ/acre (sugar and bagasse)
Corn	8 tons/acre 405 gal/acre - grain 420 gal/acre – corn stover	36 GJ/acre (starch to ethanol only) 72 GJ/acre (grain and corn stover)
Algae	32 tons/acre (20 gm/m^2/day @15%) 1267 gallons/acre	162 GJ/acre (oil only)
	49 tons/acre (30 gm/m^2/day @15%) 1899 gallons/acre	243 GJ/acre (oil only)
	49 tons/acre (30 gm/m^2/day @ 30%) 3799 gallons/acre	486 GJ/acre (oil only)

Resource Requirements





	Soybean	Algae*
gal/year	3 billion	3 billion
gal/acre	48	1267
Total acres	62.5 million**	2.4 million
Water usage	ND	6 trillion gal/yr***
CO_2 fixed	ND	79 million tons/yr

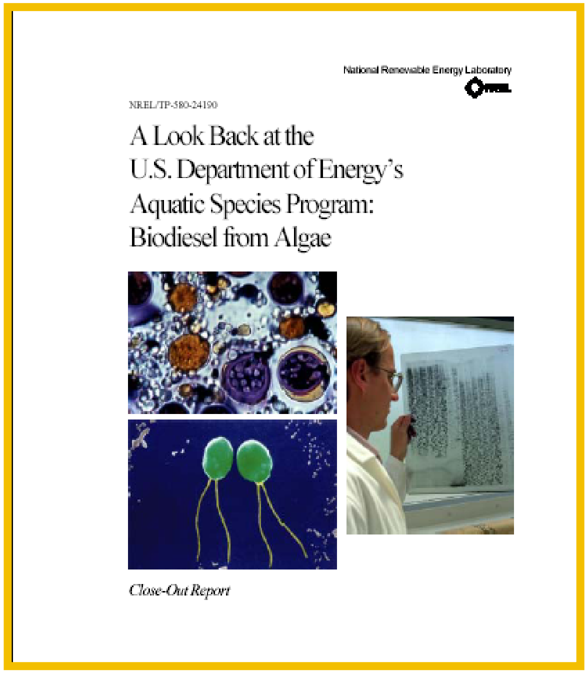
* algae (open ponds) productivity of 10 $g/m^2/day$ with 30% TAG.

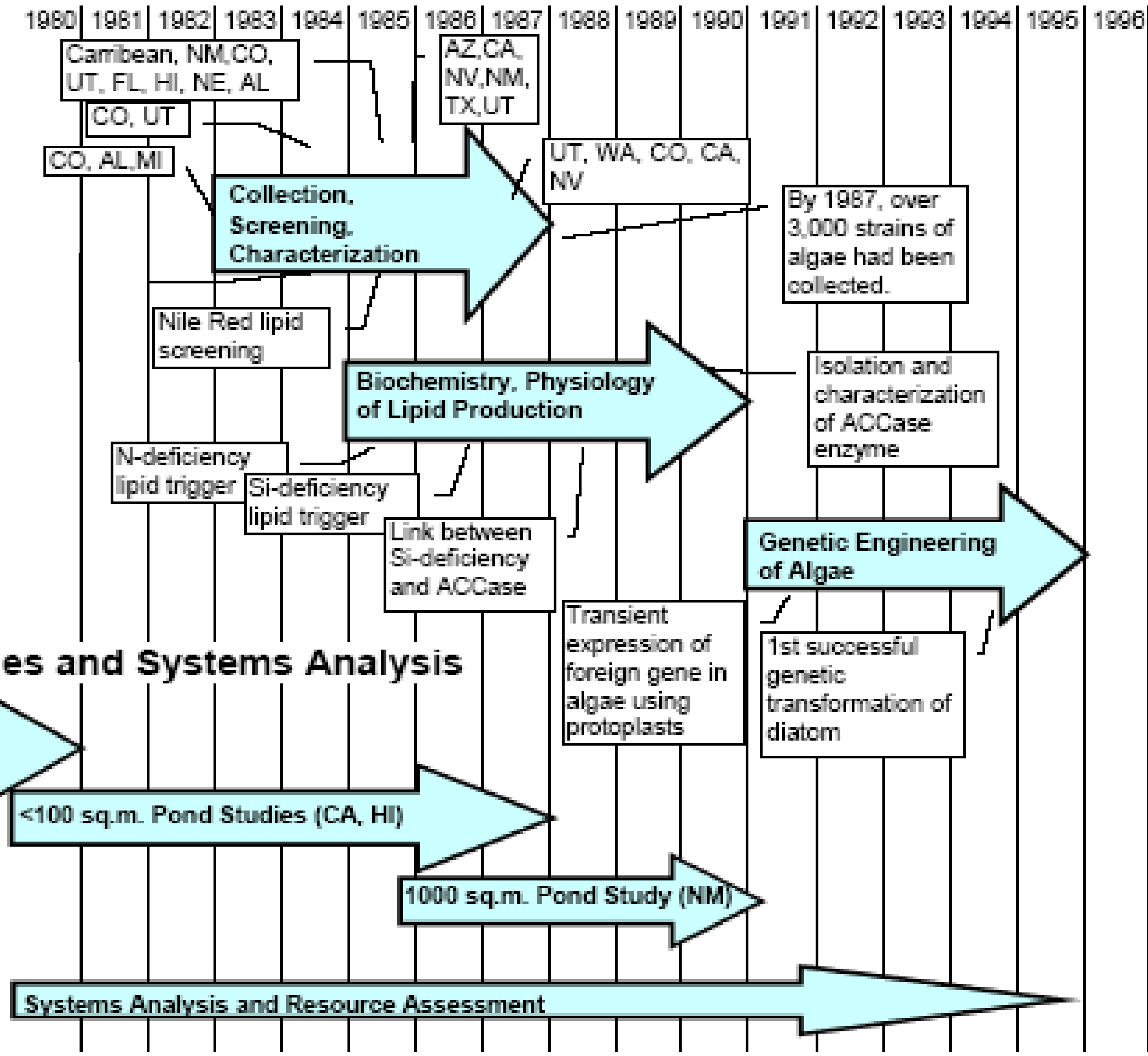
** Total land area: 73 million acres

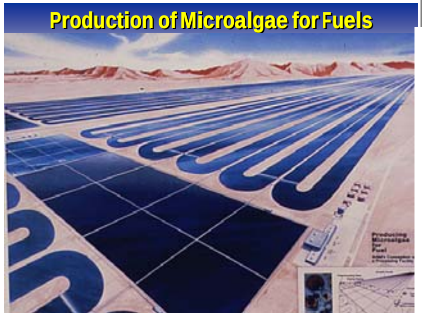
*** 50 trillion gallons used annually for irrigation of crops in the US

- World emits ~ 32 Gt CO_2 ; ~17 Gt is absorbed;15 Gt remains in atmosphere
- 1 Gt CO_2 can produce ~40 B gallons algal oil
- Average coal power plant (600-700 MW) produces 4M tons CO_2 per year

DOE's Aquatic Species Program

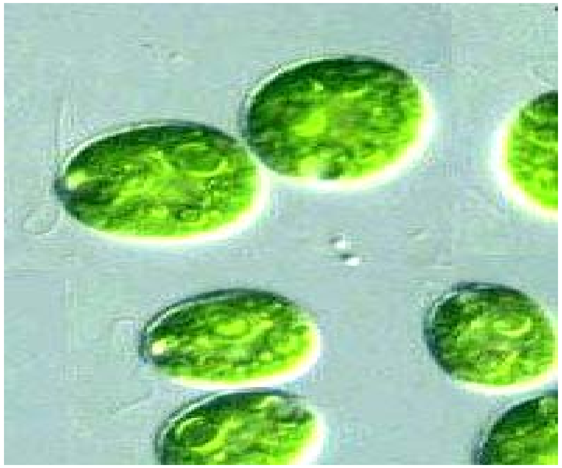




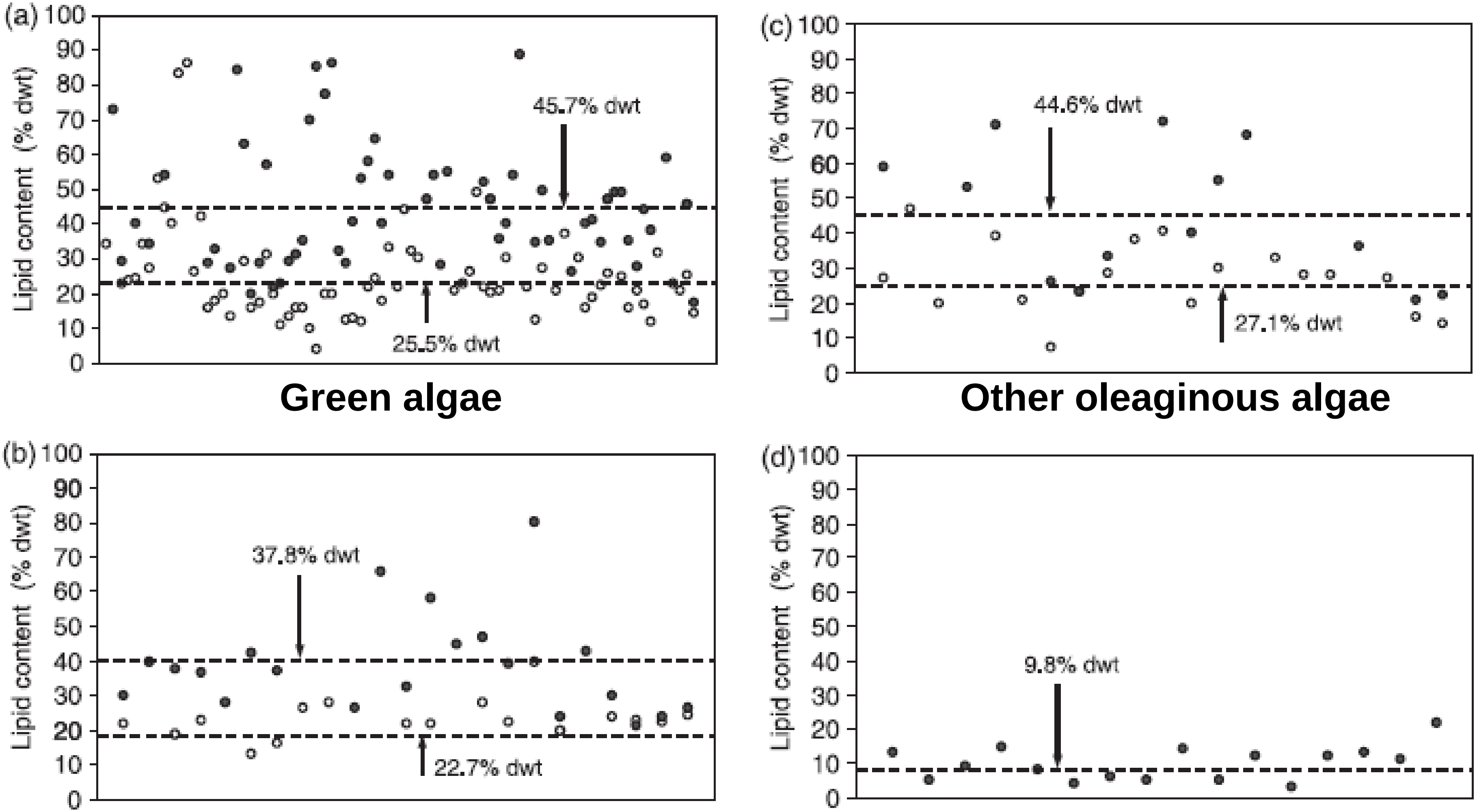


Microalgae Collection and Screening: Lessons Learned

- 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



Green algae

Other oleaginous algae

Diatoms

Cyanobacteria

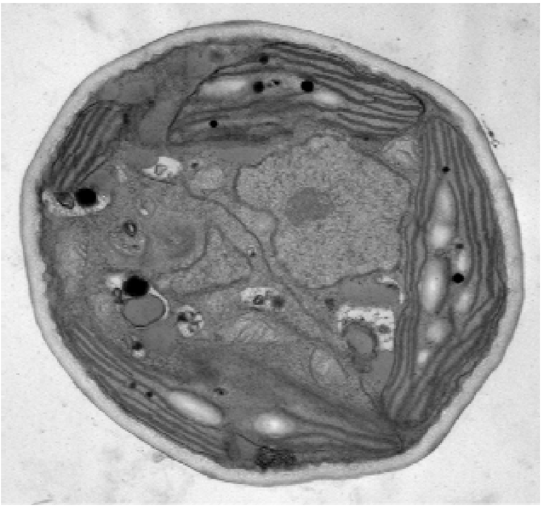
Hu, Q., Sommerfeld, M., Jarvis, E., Ghirardi, M., Posewitz, M., Seibert, M. and Darzins, A. (2008) Microalgal triacylglycerols as feedstocks for biofuel production: perspectives and advances. The Plant Journal 54:621-639.

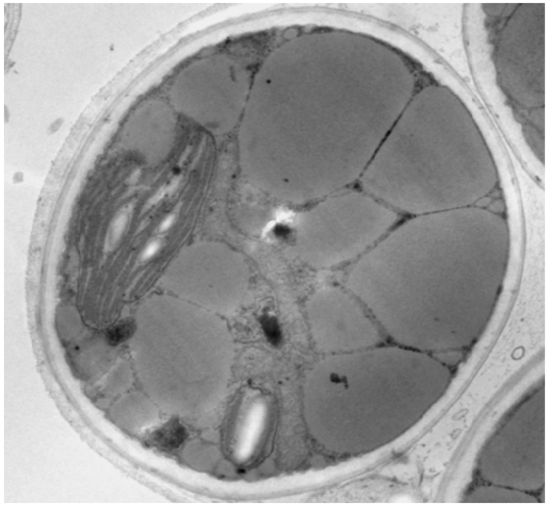
Physiology, Biochemistry, and Genetic Engineering: Lessons Learned

- 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

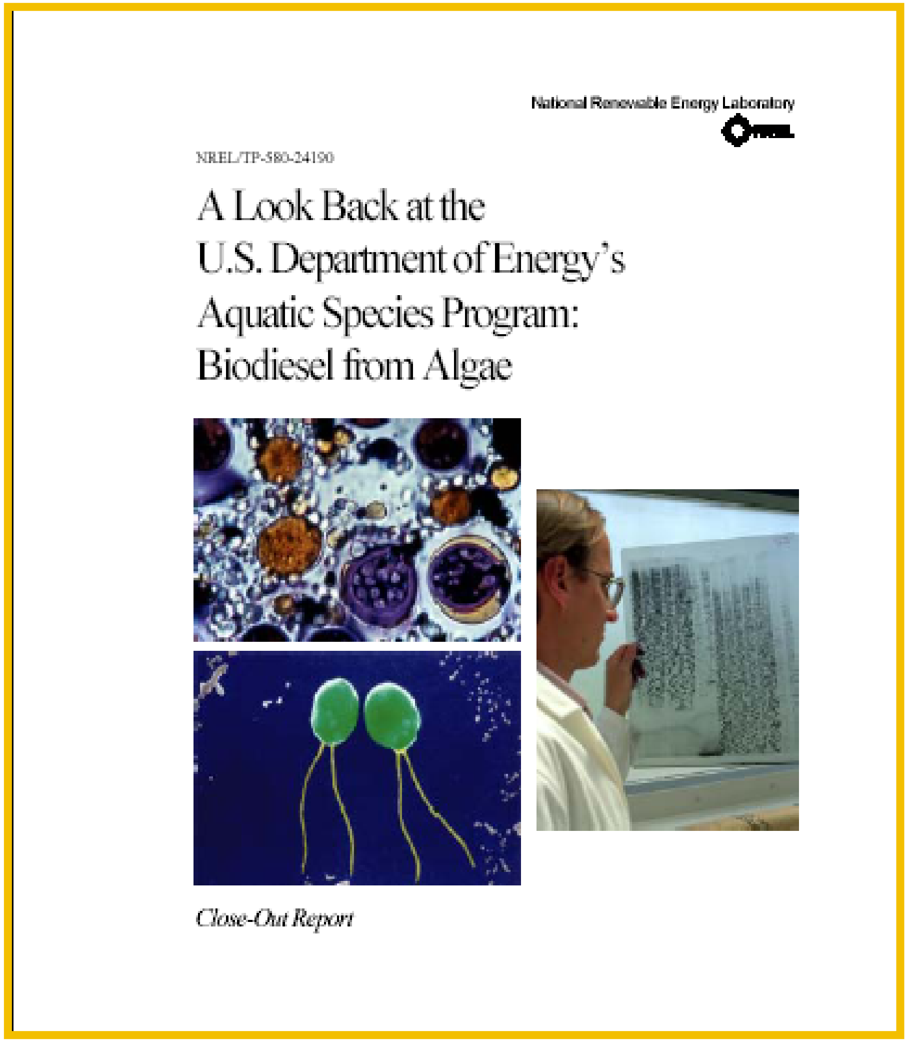




Photos courtesy: Q. Hu, ASU

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

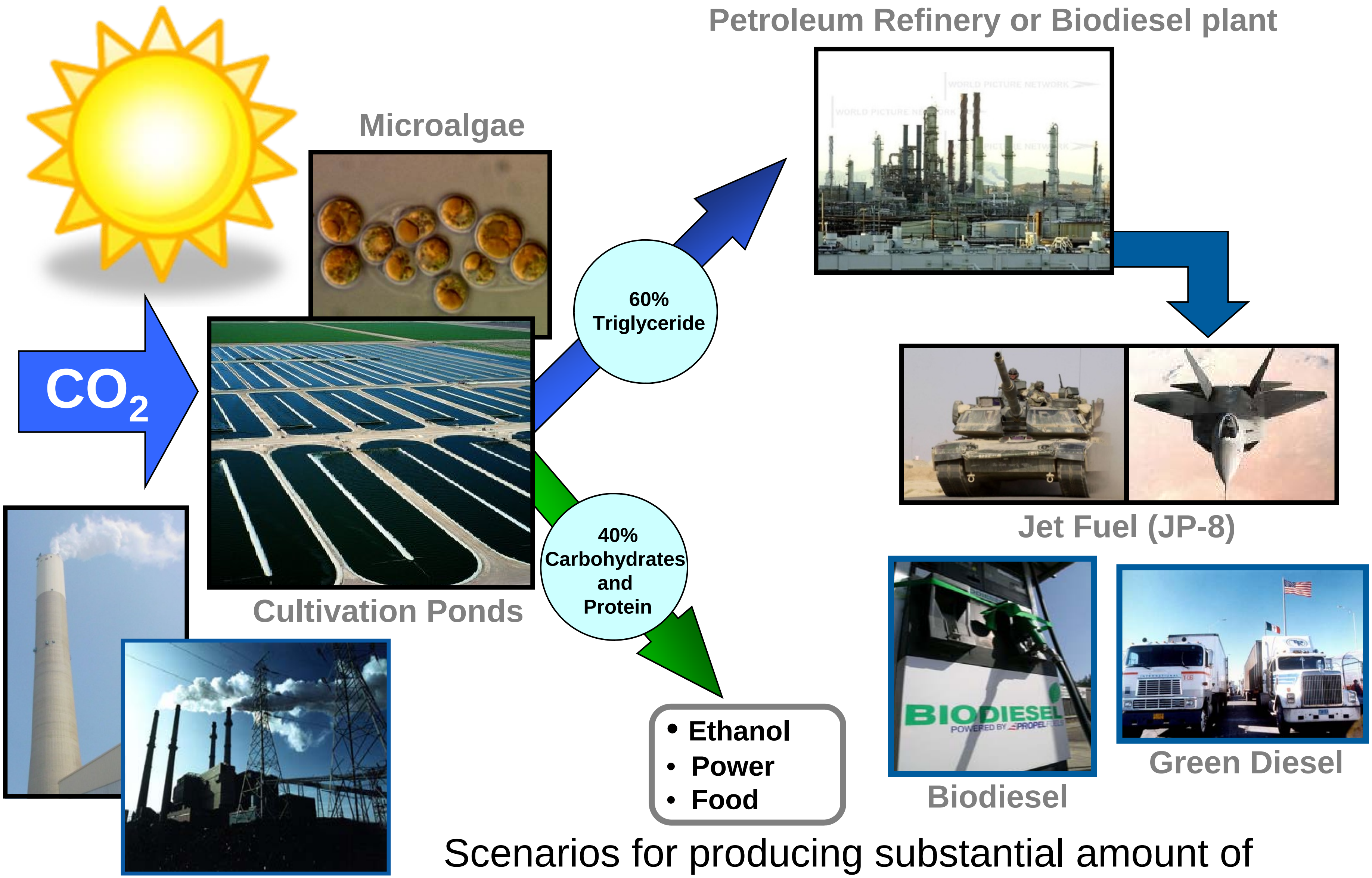


http://www.nrel.gov/docs/legosti/fy98/24190.pdf

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)
- CO_2 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

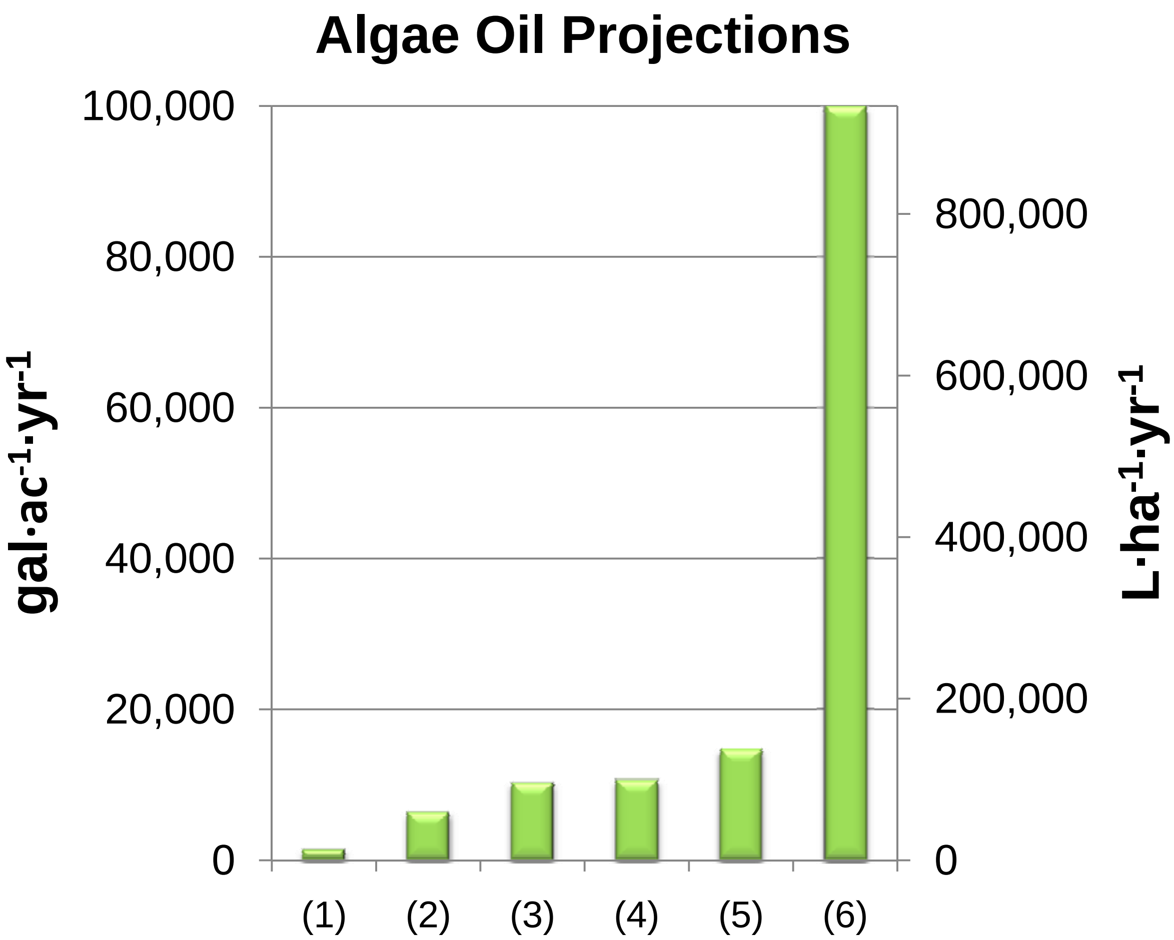
- **Harvesting**
- **De-watering methods**
- **Lipid extraction**
- Purification
- Costs, energy input
- Environmental issues
- Value from residual biomass

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

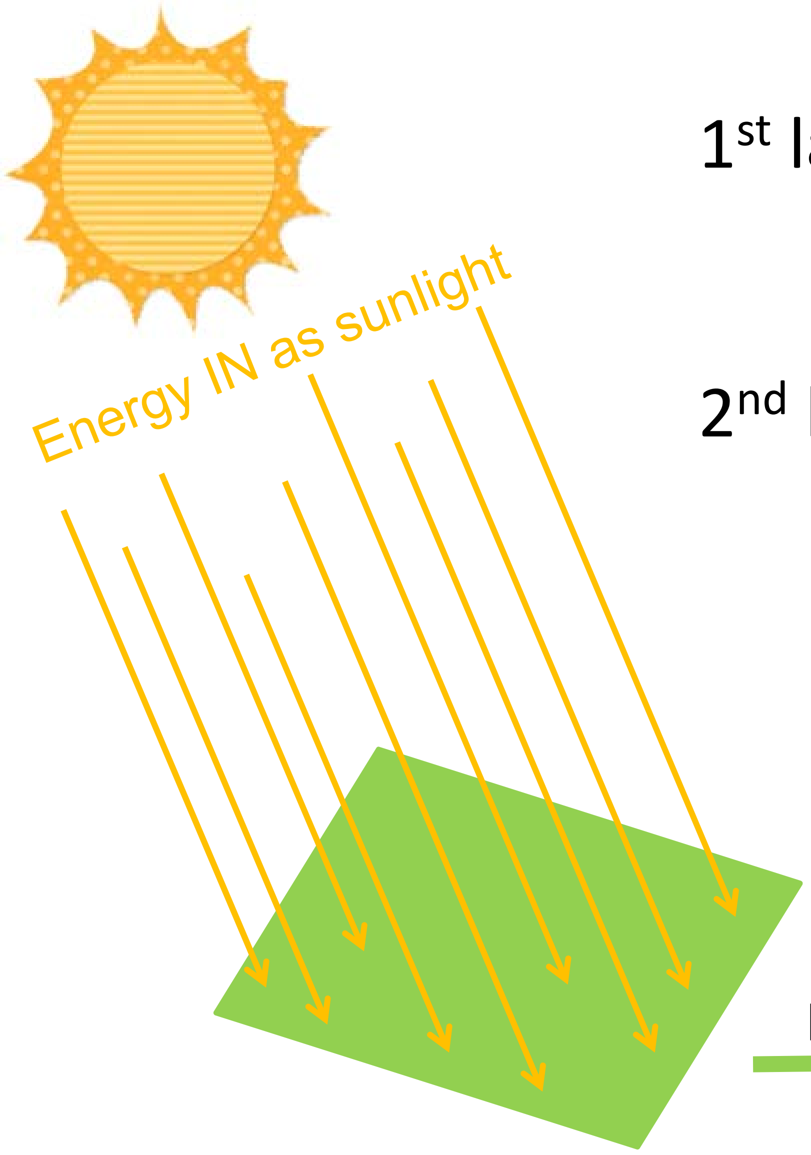


Wide range of projections…

What is the ultimate upper limit?

(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



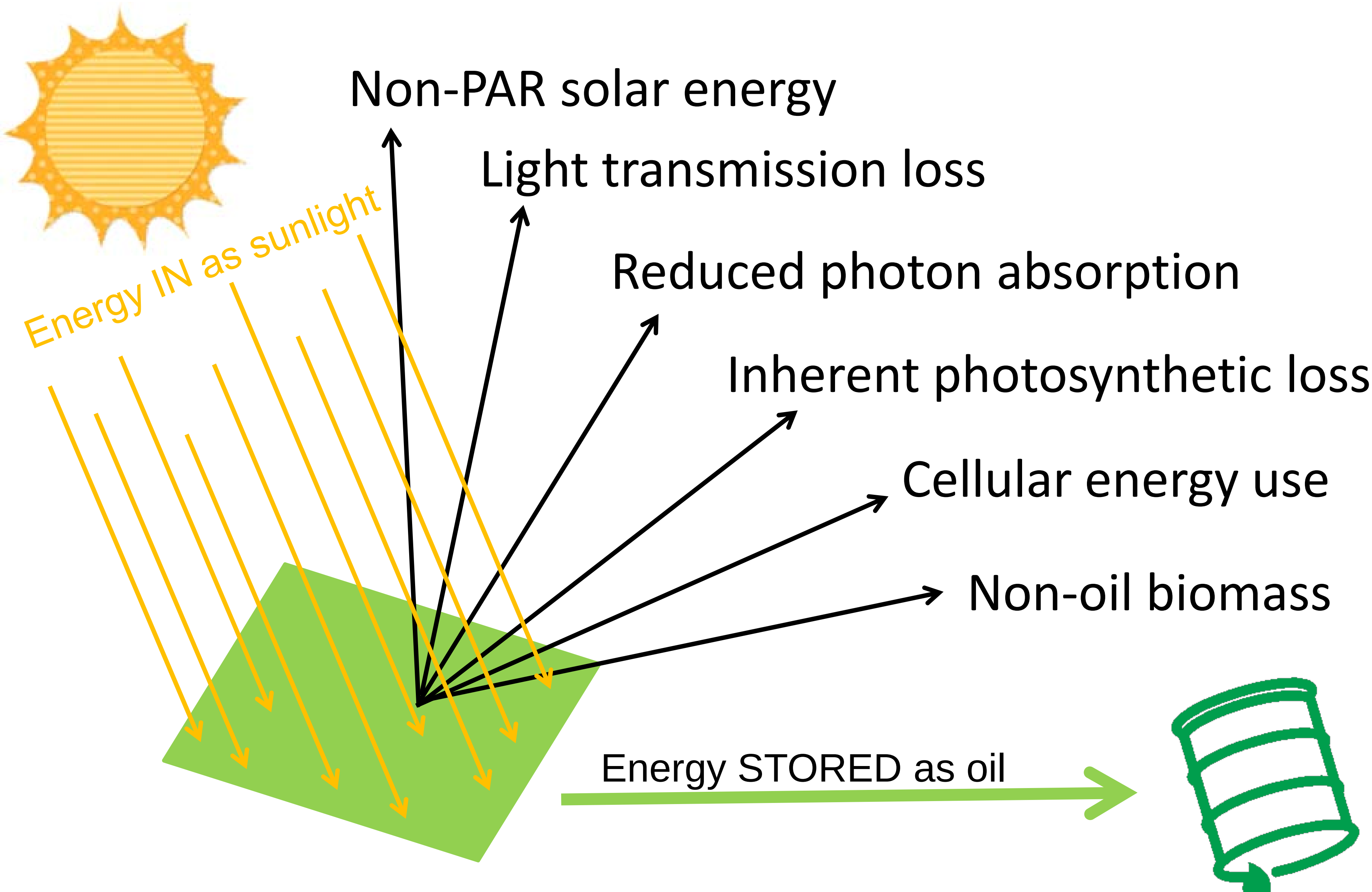
1st law: conservation of energy

$$E_{in} - E_{out} = E_{stored}$$

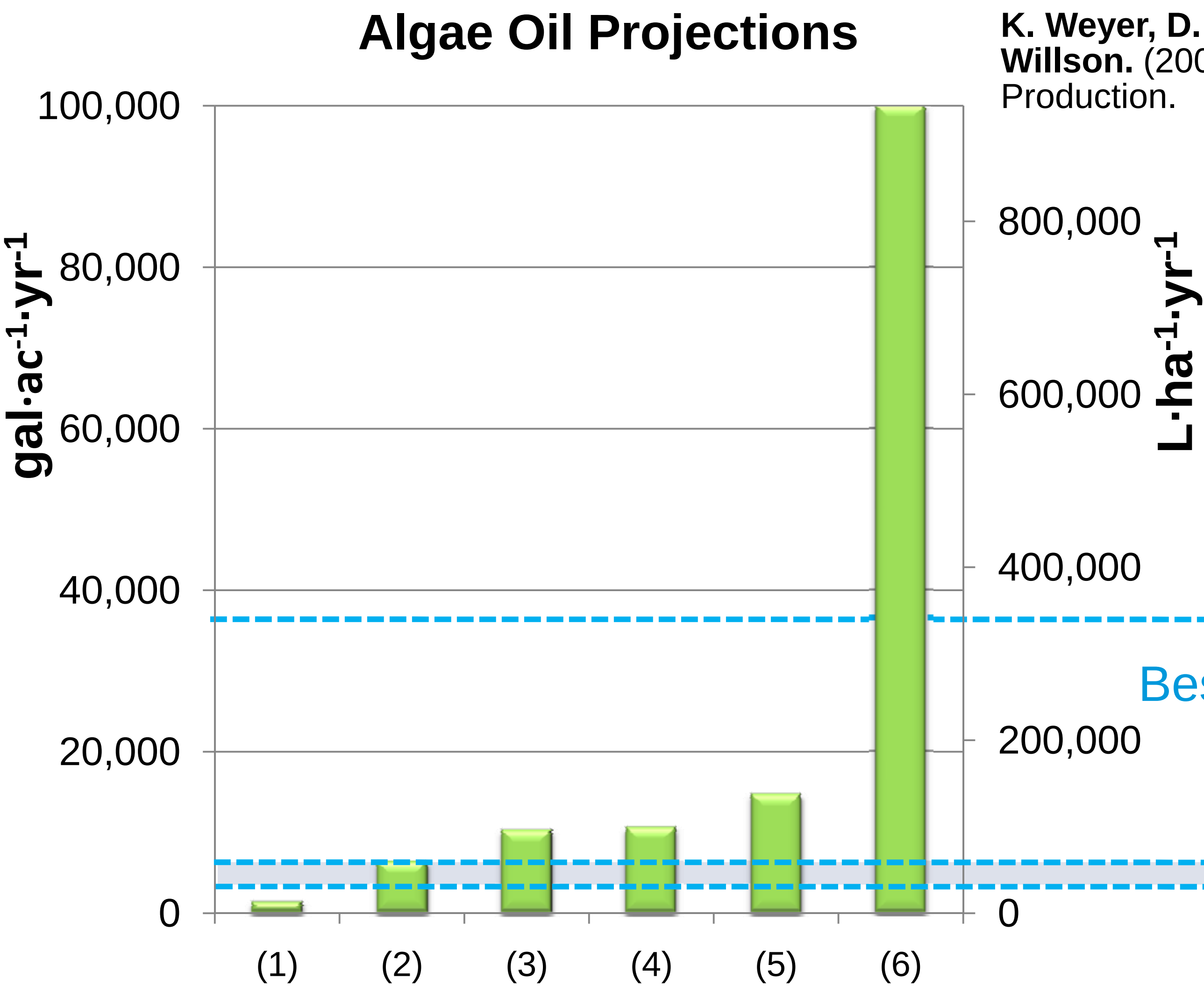
2nd law: 100% efficiency is not possible

$$E_{in} > E_{stored}$$

Inefficiences galore.....



Industry needs to well grounded….



K. Weyer, D. Bush, A. Darzins and B. Willson. (2009). Theoretical Maximum Algal Oil Production. (BioEnergy Research, in press)

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}

(1) Schenk, 2008
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(3) NREL ASP, Sheehan et al., 1998
(4) Schenk, 2008
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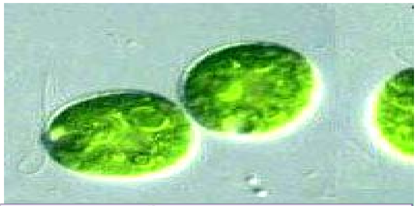
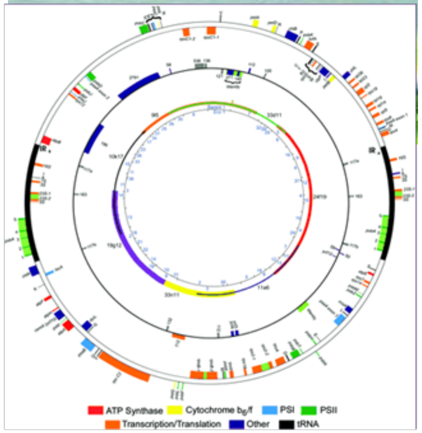
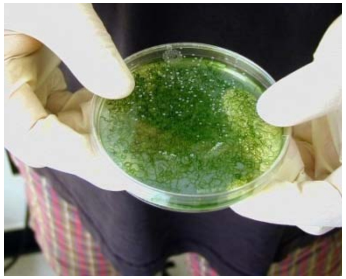
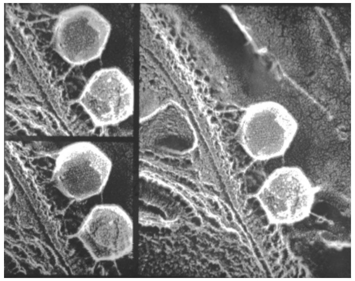
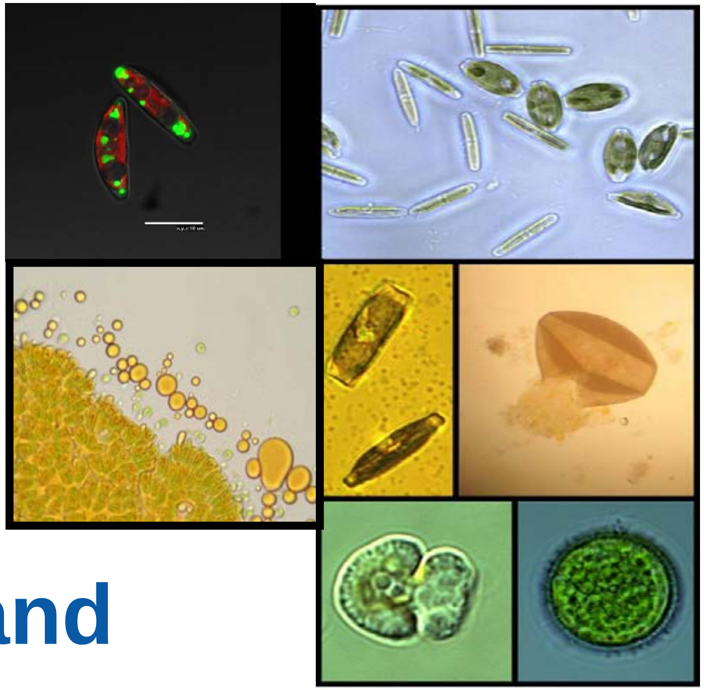


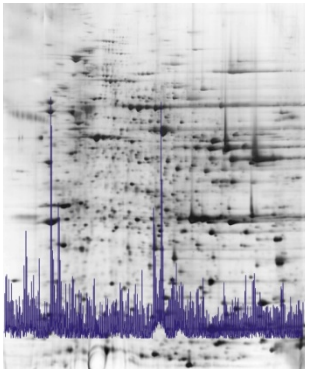


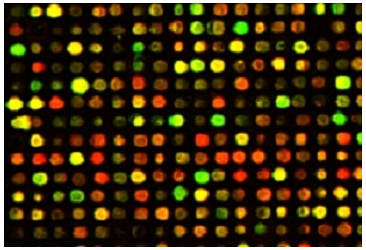


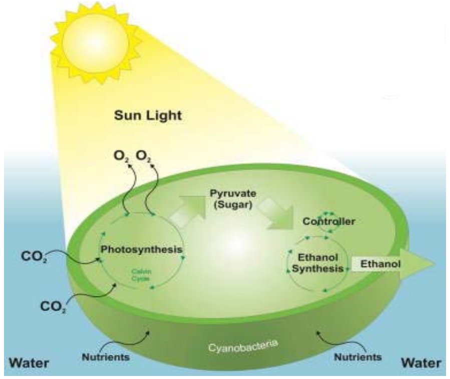


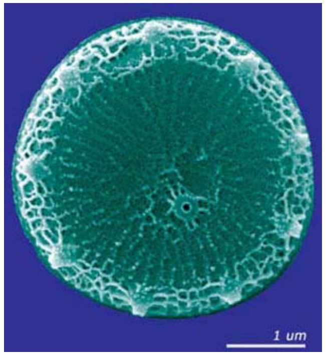


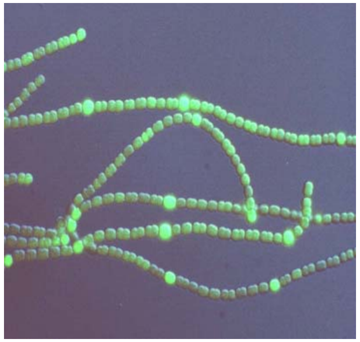
Recent Algal Biofuels Reports and Roadmapping Activities











Congressional Algae Report

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 <u>microalgae</u> 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

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

UNITED STATES AIR FORCE

AF OFFICE OF SCIENTIFIC RESEARCH

NREL

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

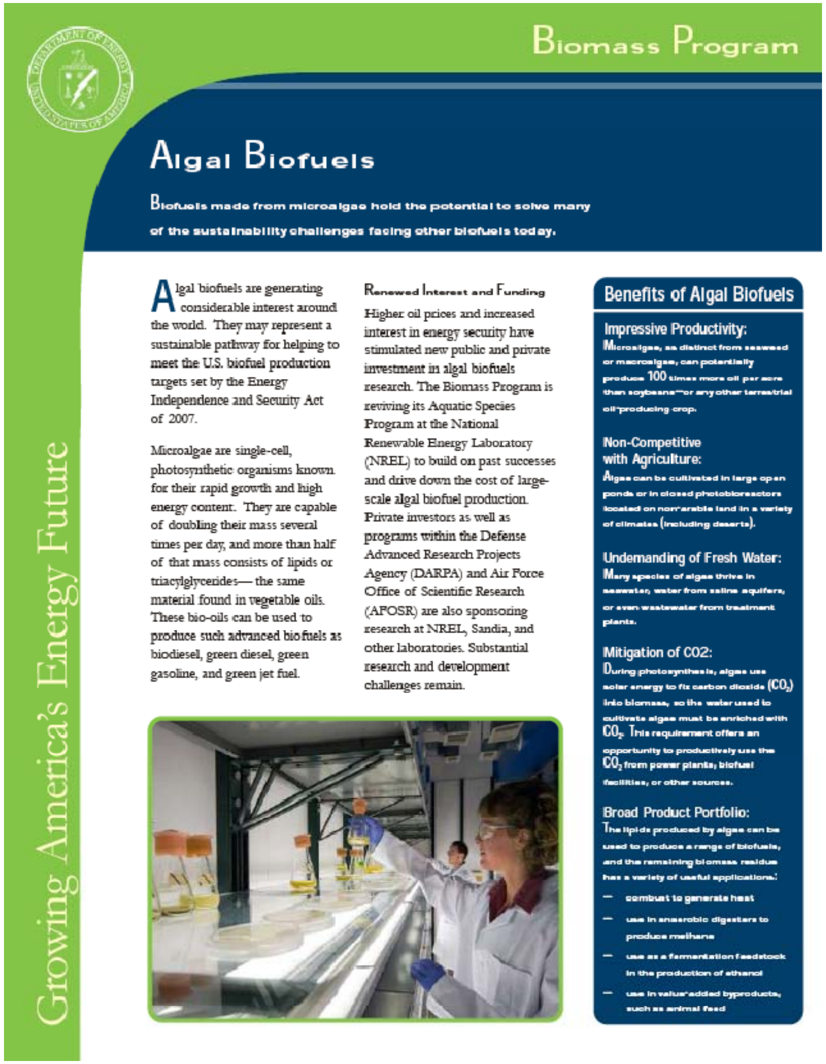
Algal Strain Research Recommendations

- **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**

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

- **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



Biomass Program

Growing America's Energy Future

Algal Biofuels

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

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.

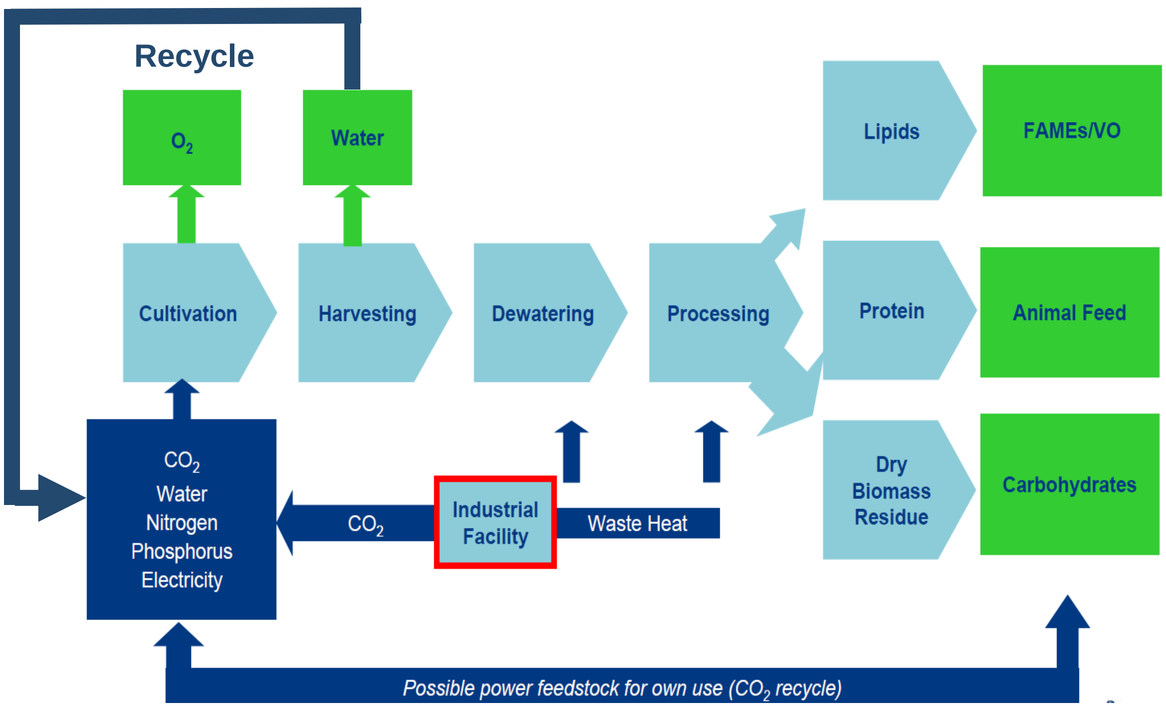
Mitigation of CO2: During photosynthesis, algae use solar energy to fix carbon dioxide (CO_2) into biomass, so the water used to cultivate algae must be enriched with CO_2. This requirement offers an opportunity to productively use the CO_2 from power plants, biofuel facilities, or other sources.

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

Fundamental and applied research needed to resolve uncertainties associated with commercial-scale algal biofuel production:

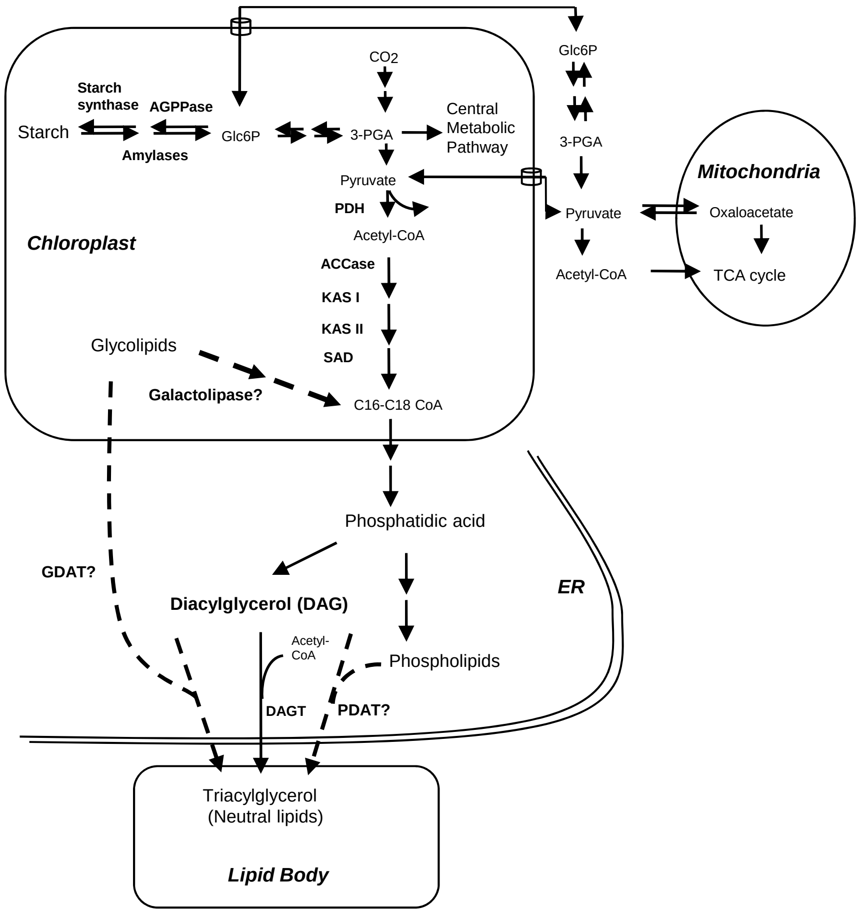


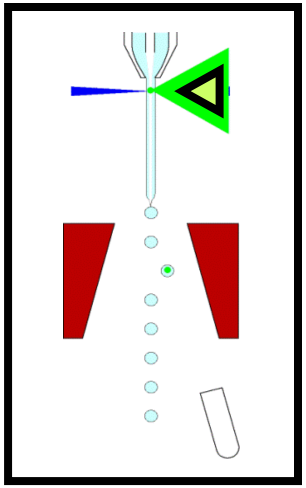
Roadmap Chapters

- **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

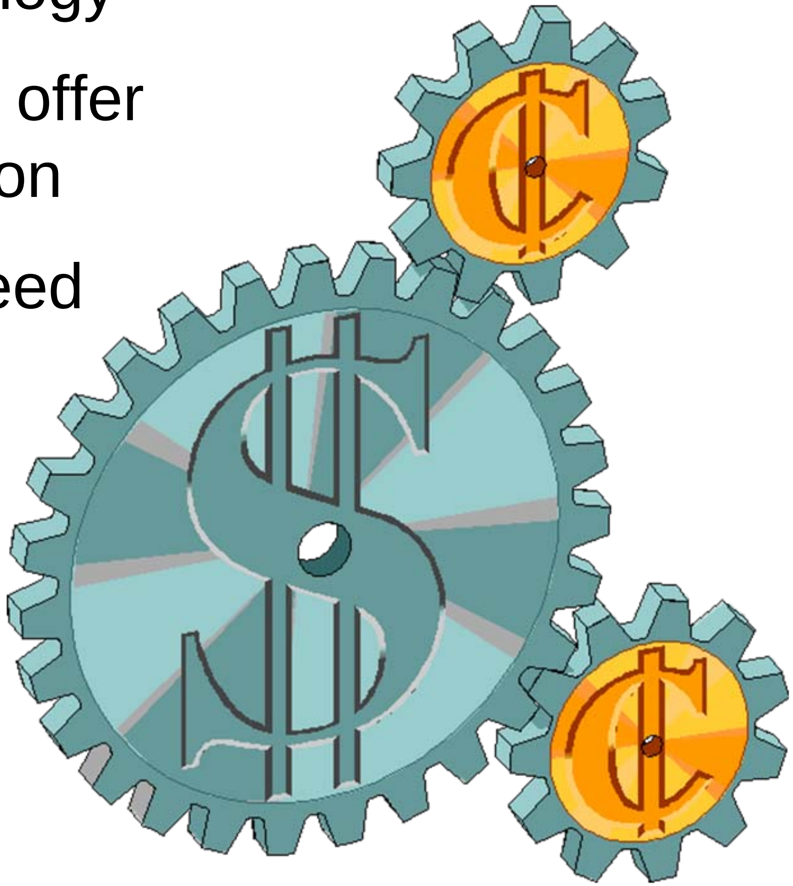
- **Strain isolation and screening**
- **Cell biology and physiology**
- **Genetic toolbox**
- **Systems biology**



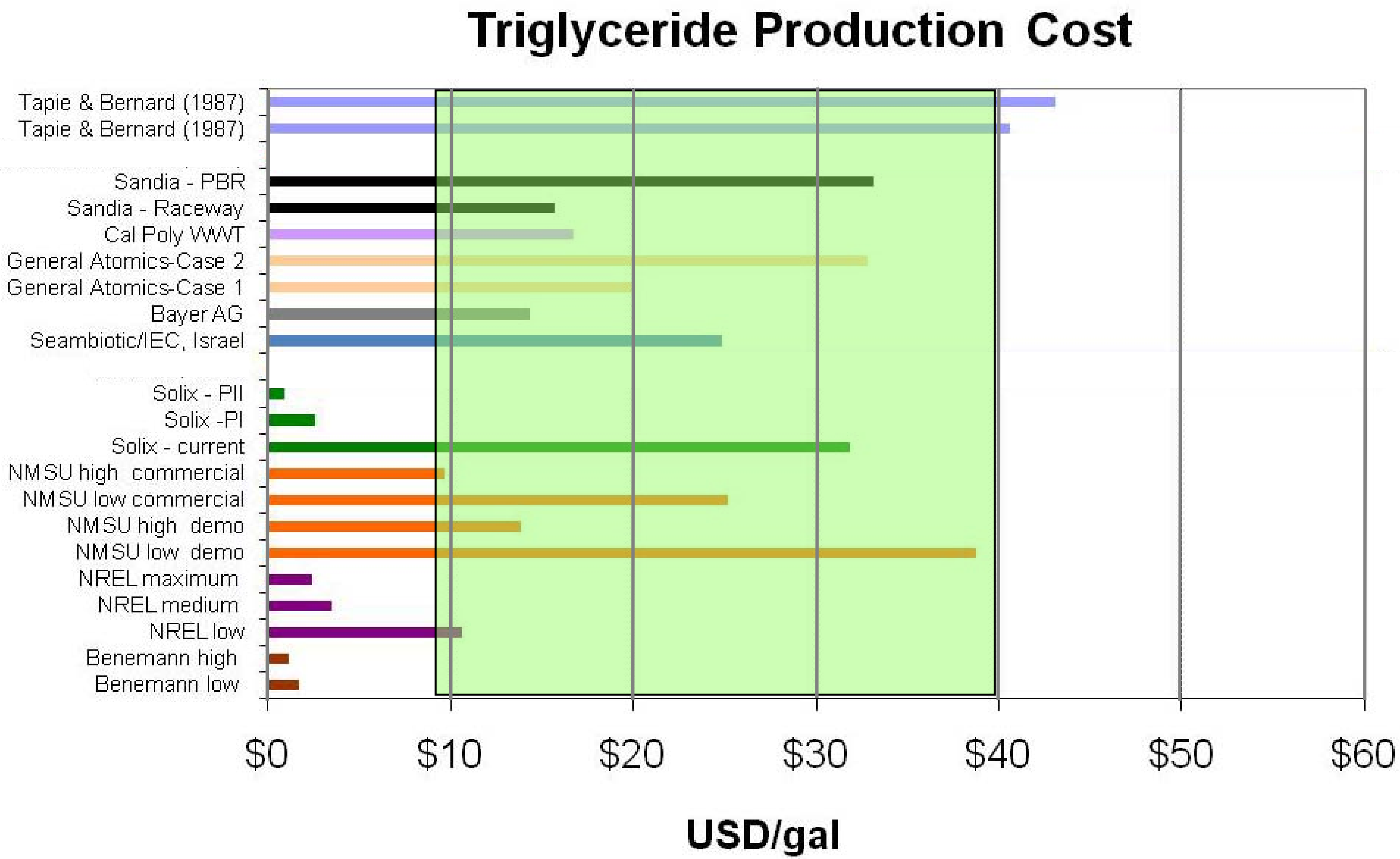


Technoeconomic Modeling

- 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



Standardized Cost Comparison



IEA Bioenergy Task 39
Algal Biofuels Technology Report

Algal Biofuels Draft Report Outline

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
- 3.5.2Technology 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
    - o Food and feed production
    - o Water remediation
    - o Job creation
    - o Education
    - o International competitiveness
- IEA Bioenergy Task 39 Algal Biofuels Report
  - opportunity to bring together the international algal biofuels efforts

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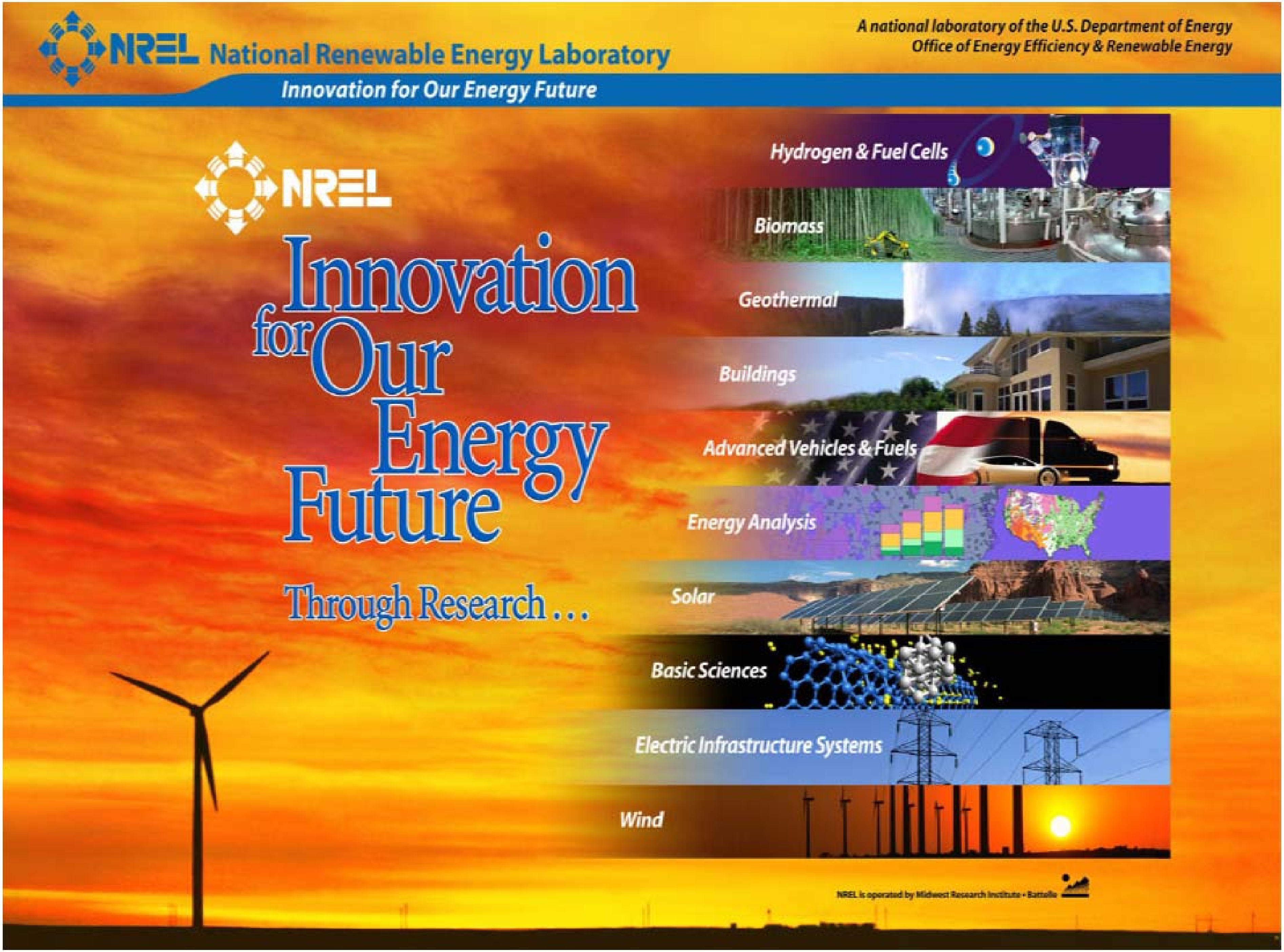
Algal biofuels research at NREL: http://www.nrel.gov/biomass/proj_microalgae.html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