Algal Feedstock-Based Biofuels: Separating Myth from Reality

NREL Power Lunch Lecture Series

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NREL C2B2 Site Director

February 18, 2009

NOTICE

Outline

Are we there yet?

Why consider algae as a transportation fuel feedstock?

DOE's former Aquatic Species Program (ASP)

Who's interested in algal biofuels?

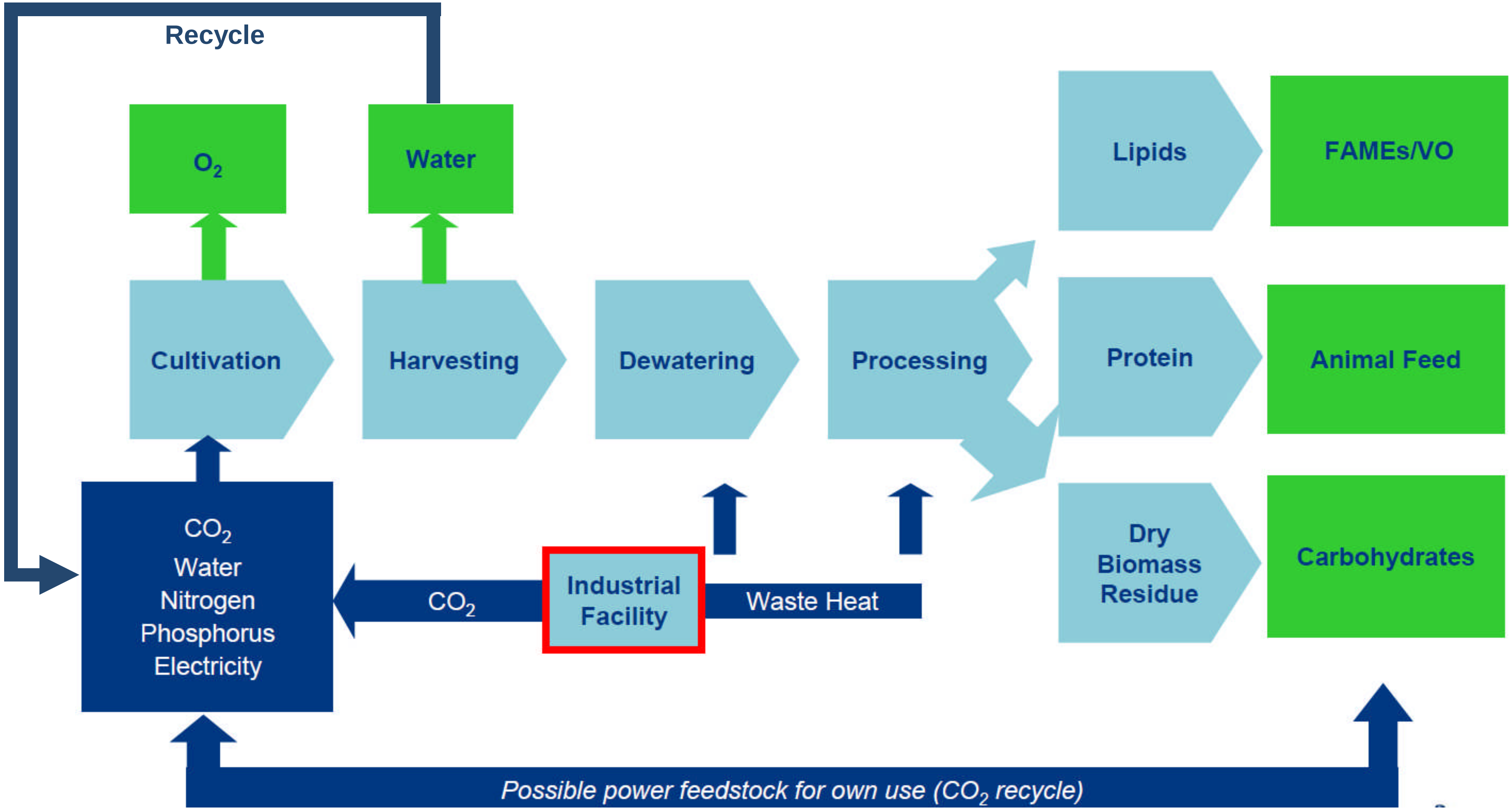
What are the challenges? (Myth vs. reality)

What R&D is needed to cross the commercial finish line?

Re-establishment of NREL's algal research program

Conclusions

General Cultivation and Processing Flow Sheet

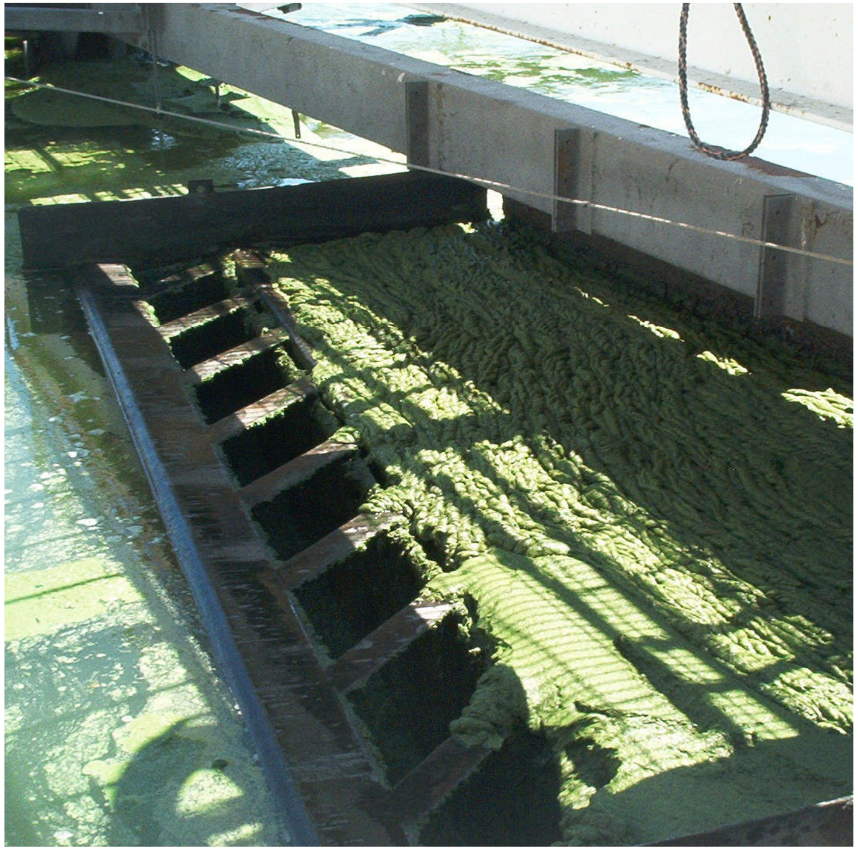


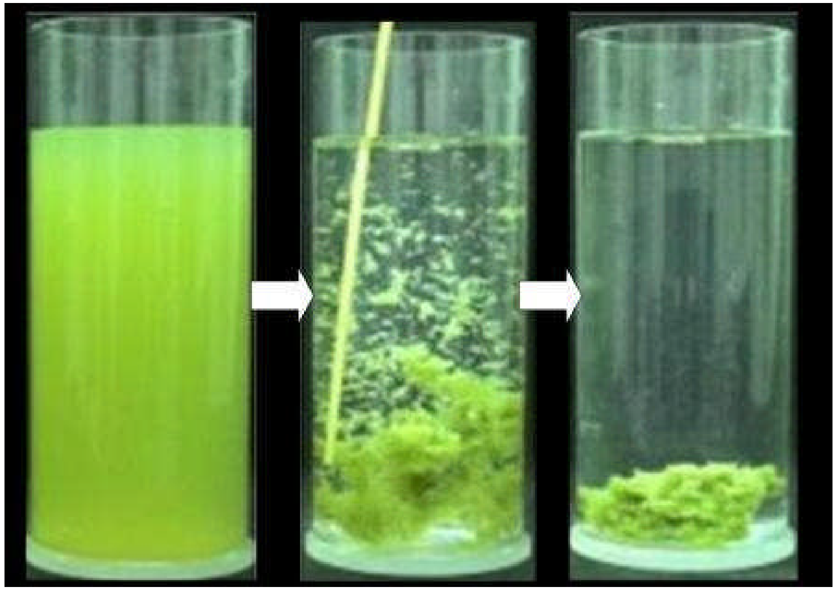
Source: Dan Anderson, PNNL

We can cultivate algae at large scale…

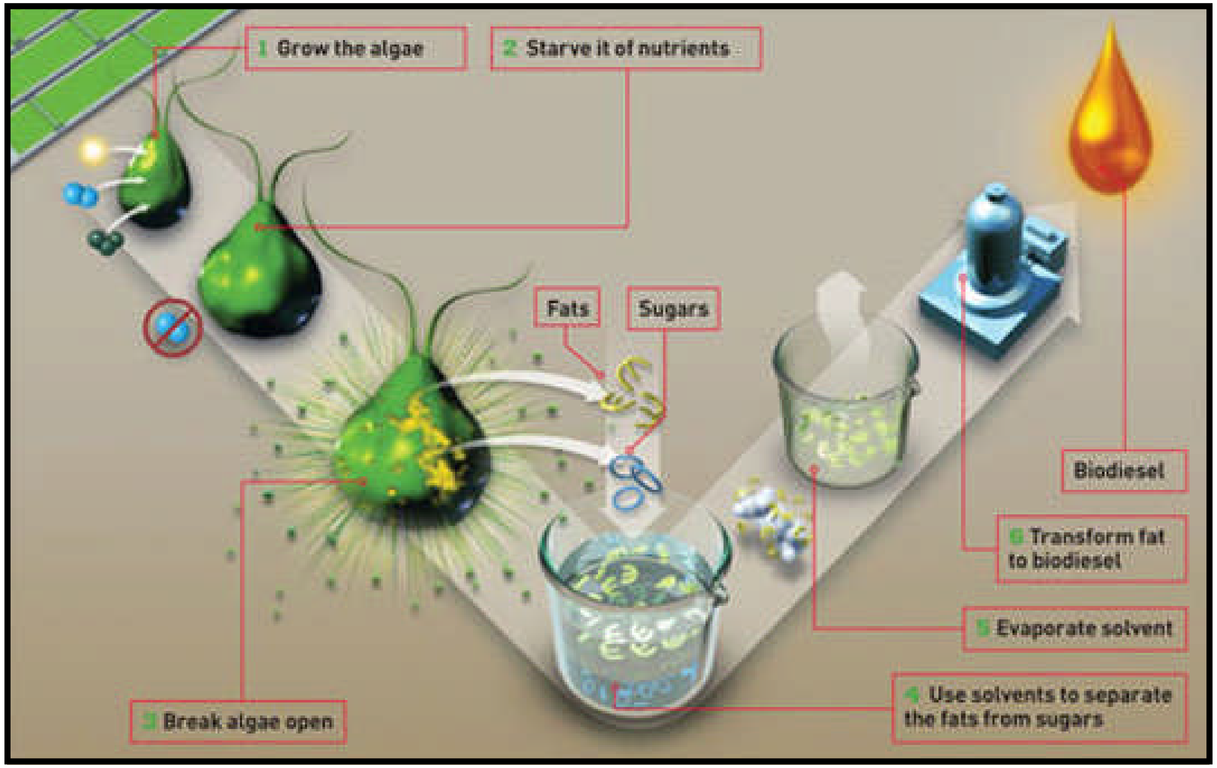
Cyanotech Corp.
Kona, Hawaii
Keahole Point

We can harvest algae….





We can extract oil from algae….



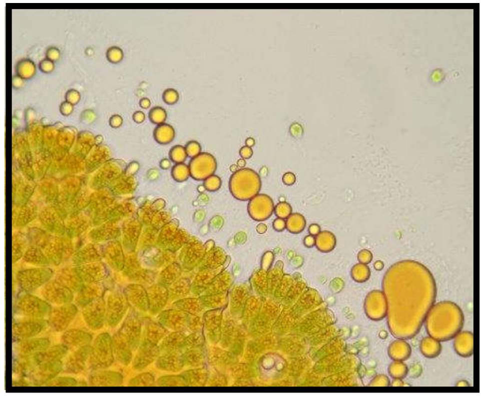


Image courtesy: Q. Hu, ASU

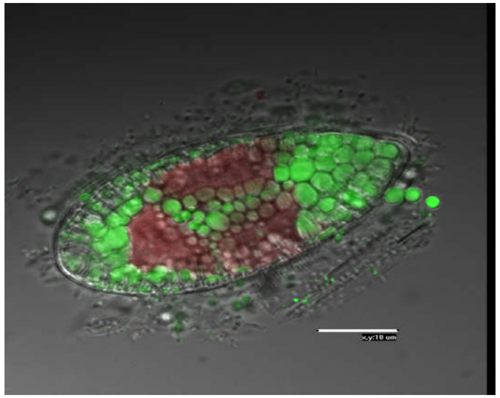


Image courtesy: Lee Elliot, CSM

We can convert algal oil to fuels….

Jan. 23, 2008

Solazyme promotes its process of making biodiesel from algae by driving a Mercedes diesel through Park City, UT during the Sundance film festival.

Jan. 7, 2009

Boeing 737-800 took off from Houston on a 2-hr test flight fueled by sustainable biofuel from algae and jatropha.

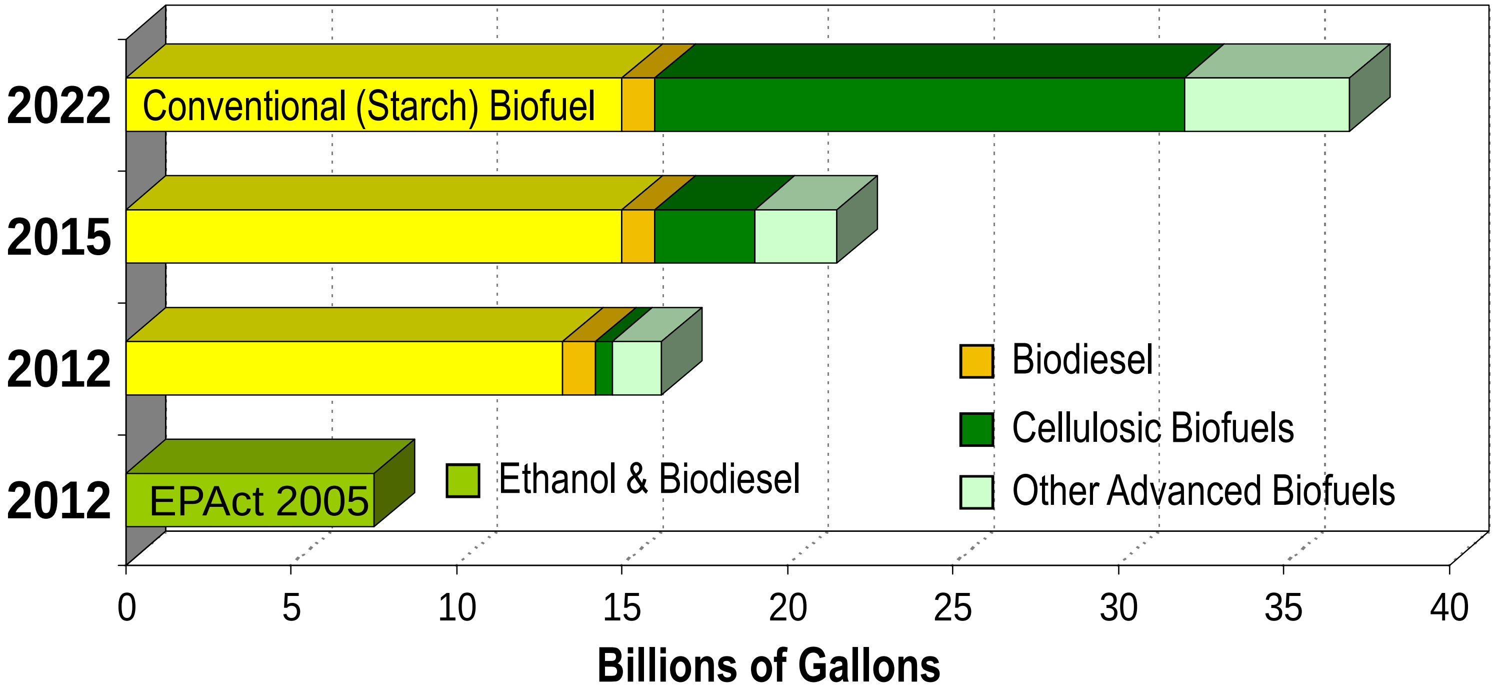
Continental Airlines

But, we cannot produce algal biofuels cost effectively today

Advanced Biofuels in 2007 EISA

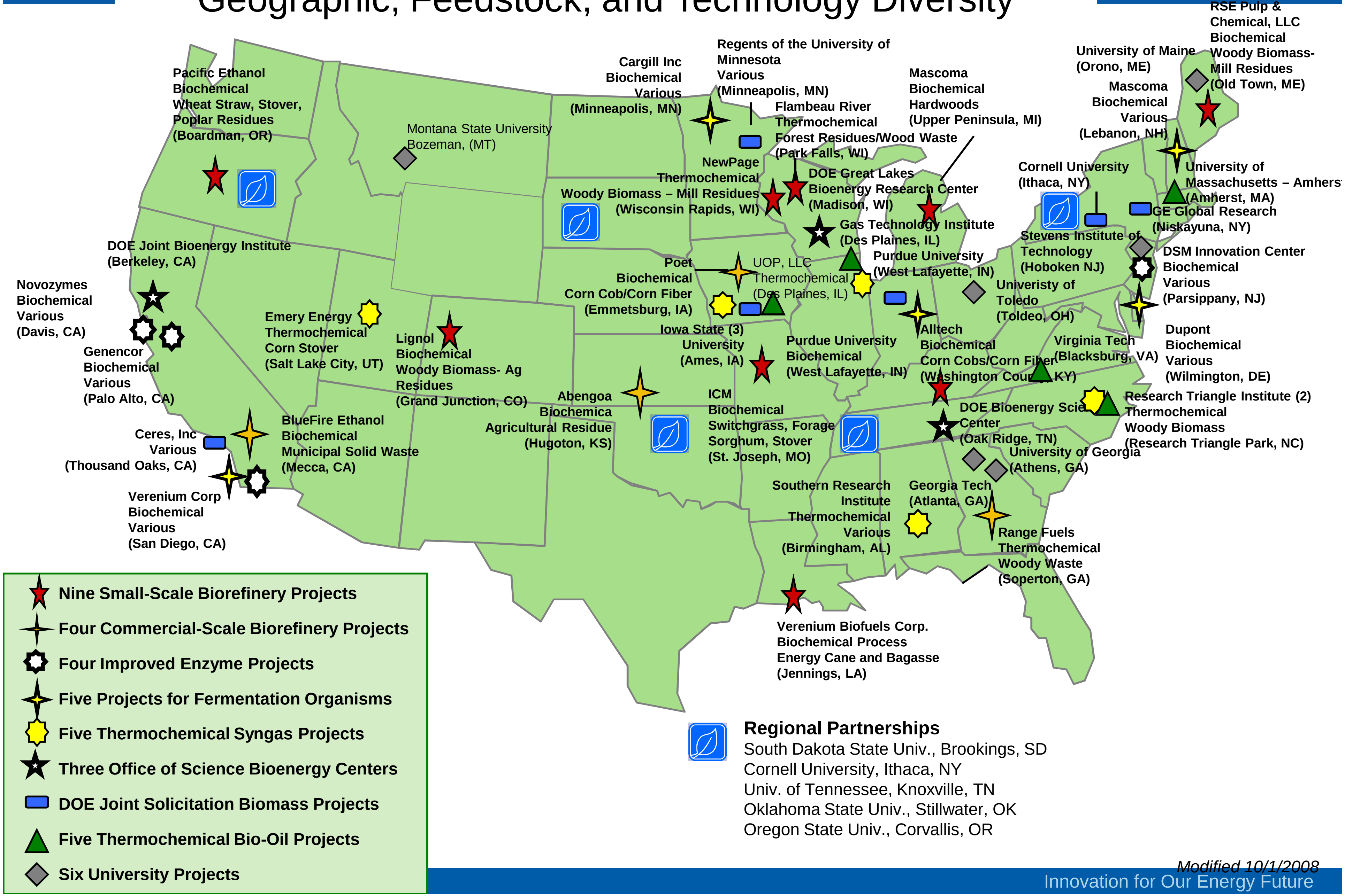
Section 202 – **Renewable Fuels Standard** sets aggressive volumetric goals

Development **must** include Advanced Biofuels that are interchangeable with traditional fuels and can be more easily integrated into the current infrastructure.



Major DOE Biofuels Project Locations

Geographic, Feedstock, and Technology Diversity



Modified 10/1/2008

Biofuel Challenges: Energy Density

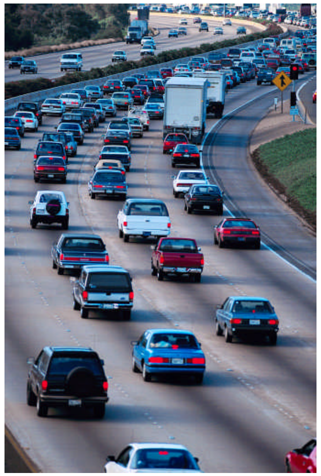
Cellulosic ethanol addresses the gasoline market

- U.S. gasoline usage: 140 billion gallons/year
- Doesn't address need for higher-energy density fuels

Energy Densities (Lower Heating Value)

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

- U.S. petroleum diesel: 66 billion gallons/year
- U.S. jet fuel: 25 billion gallons/year



The Biodiesel Dilemma

Triglycerides (TAGs) from oilseed crops/waste oils can't meet U.S. diesel demand (60+ billion gal/yr)

– ~ 3 billion gallons soy oil/year (US)

– Replaces only 5% of petroleum diesel fuel usage.

– Cost of biodiesel feedstock increasing

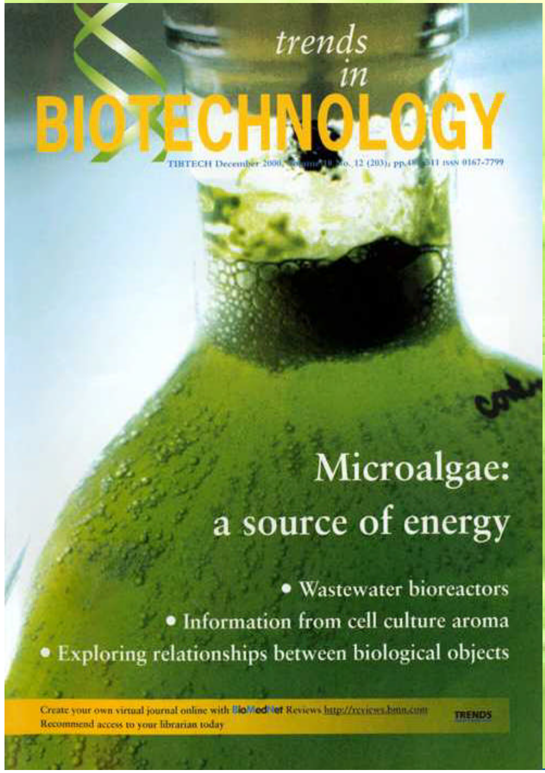
- High: $0.63/lb; $4.80/gallon
- Current: $0.33/lb; $2.54/gallon

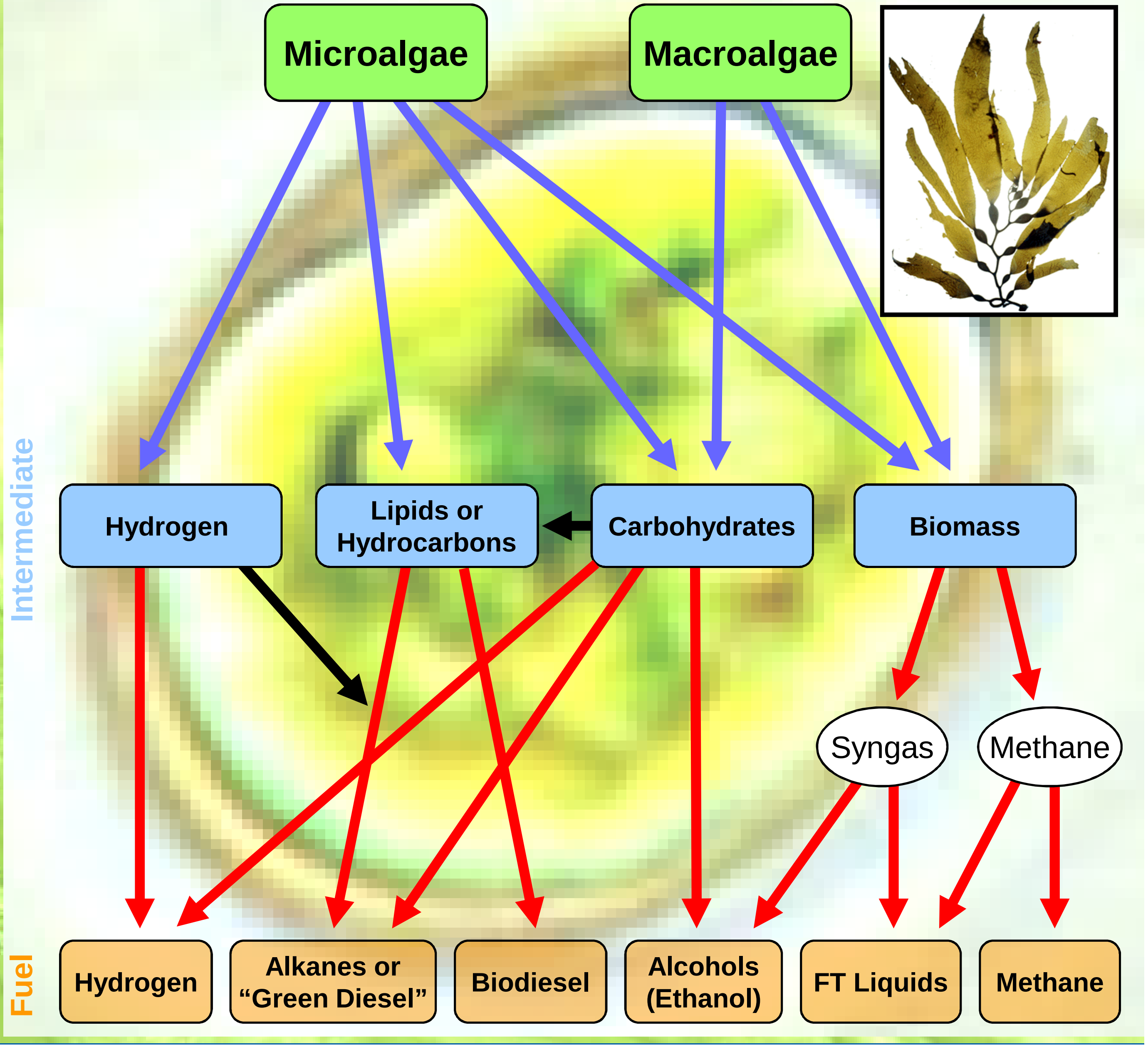
– Input costs high – competes with high valued food market

Alternative sources of TAGs are needed!

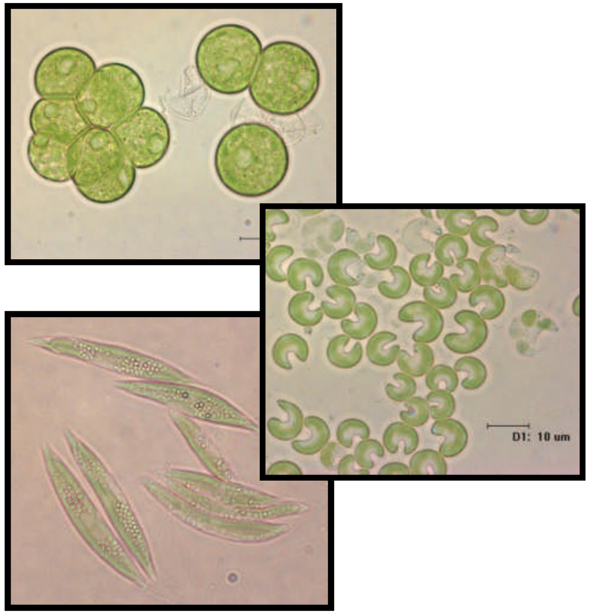
Algae: Numerous Bioenergy Routes

Defining a Biofuels Portfolio From Microalgae



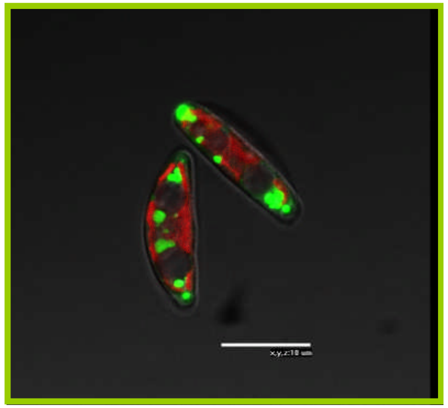


Why Fuels from Algal Oil?



Images courtesy:
Lee Elliott, CSM

- High-lipid content (60%); rapid growth rates; more lipids than terrestrial plants --*10x - 100x*
- Can use non-arable land; saline/brackish water
- No competition with food or feed
- Utilize large waste CO_2 resources (i.e., flue gas)
- Potential to displace significant U.S. petroleum fuel usage



Fluorescence micrograph showing stained algal oil droplets (green)

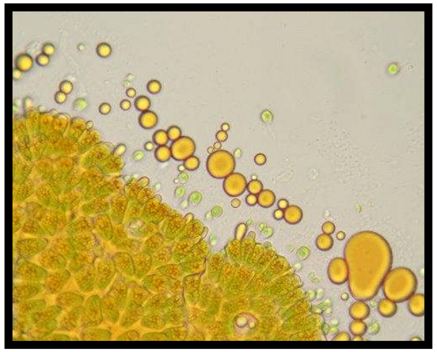
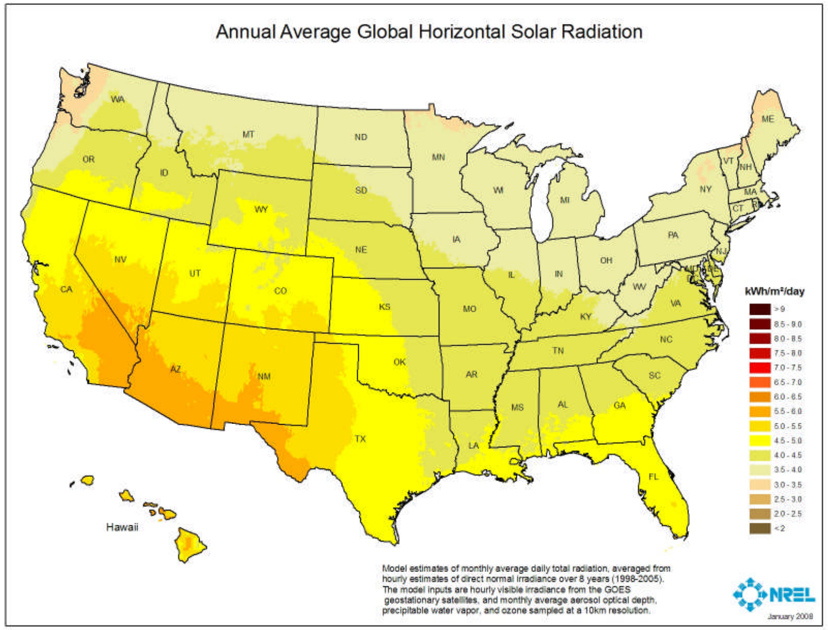


Image courtesy: Q. Hu, ASU



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 (10g/m^2/day-15%)	1200
Algae (50g/m^2/day-50%)	10,000

Image courtesy: Q. Hu, ASU

Resource Requirements

	Soybean	Algae*
gal/year	3 billion	3 billion
gal/acre	48	1200
Total acres	62.5 million	2.5 million
Water usage	ND	6 trillion gal/yr
CO_2 fixed	ND	70 million tons/yr
Price per gallon	$2.54	>$9-36

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

CO_2 Capture Potential

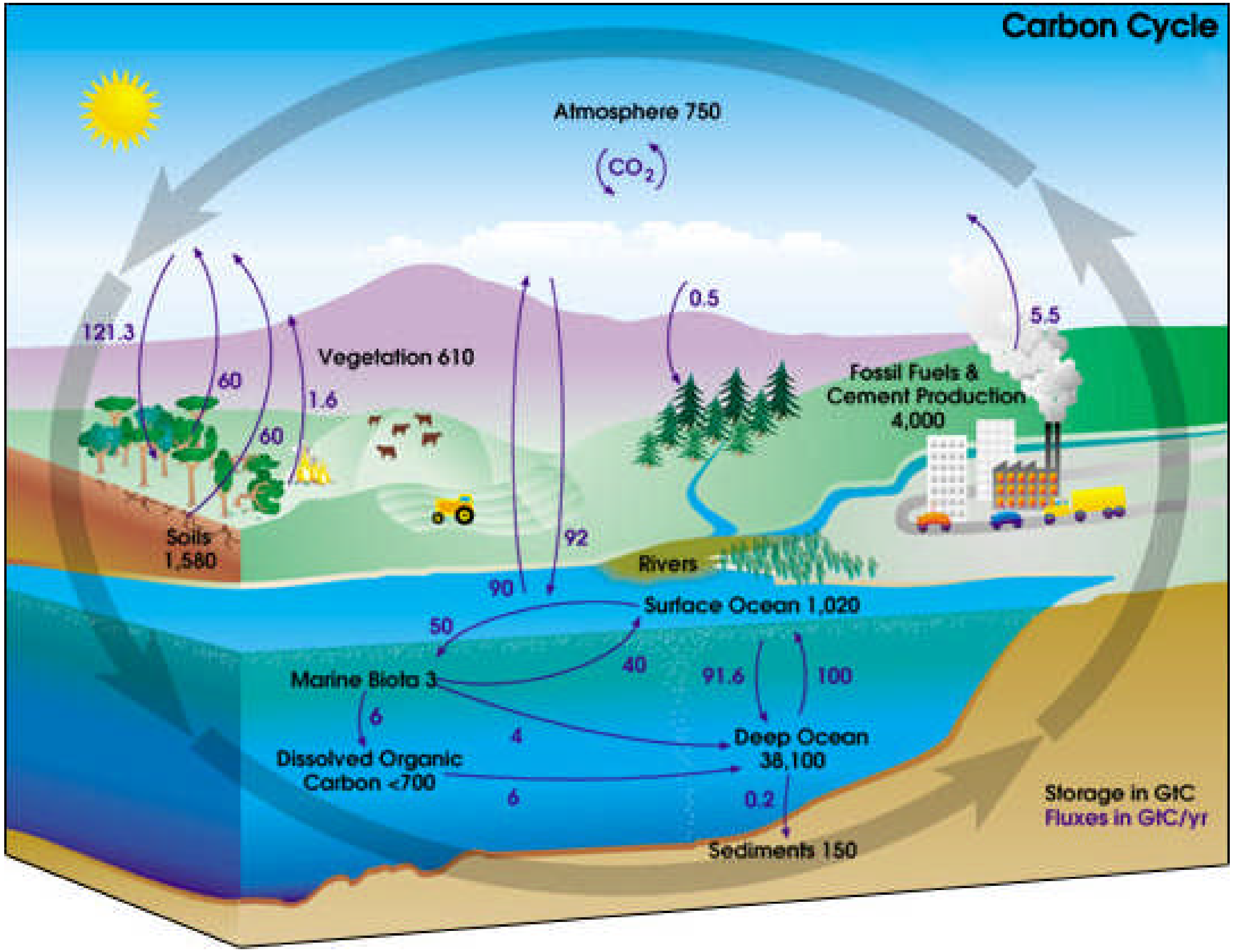
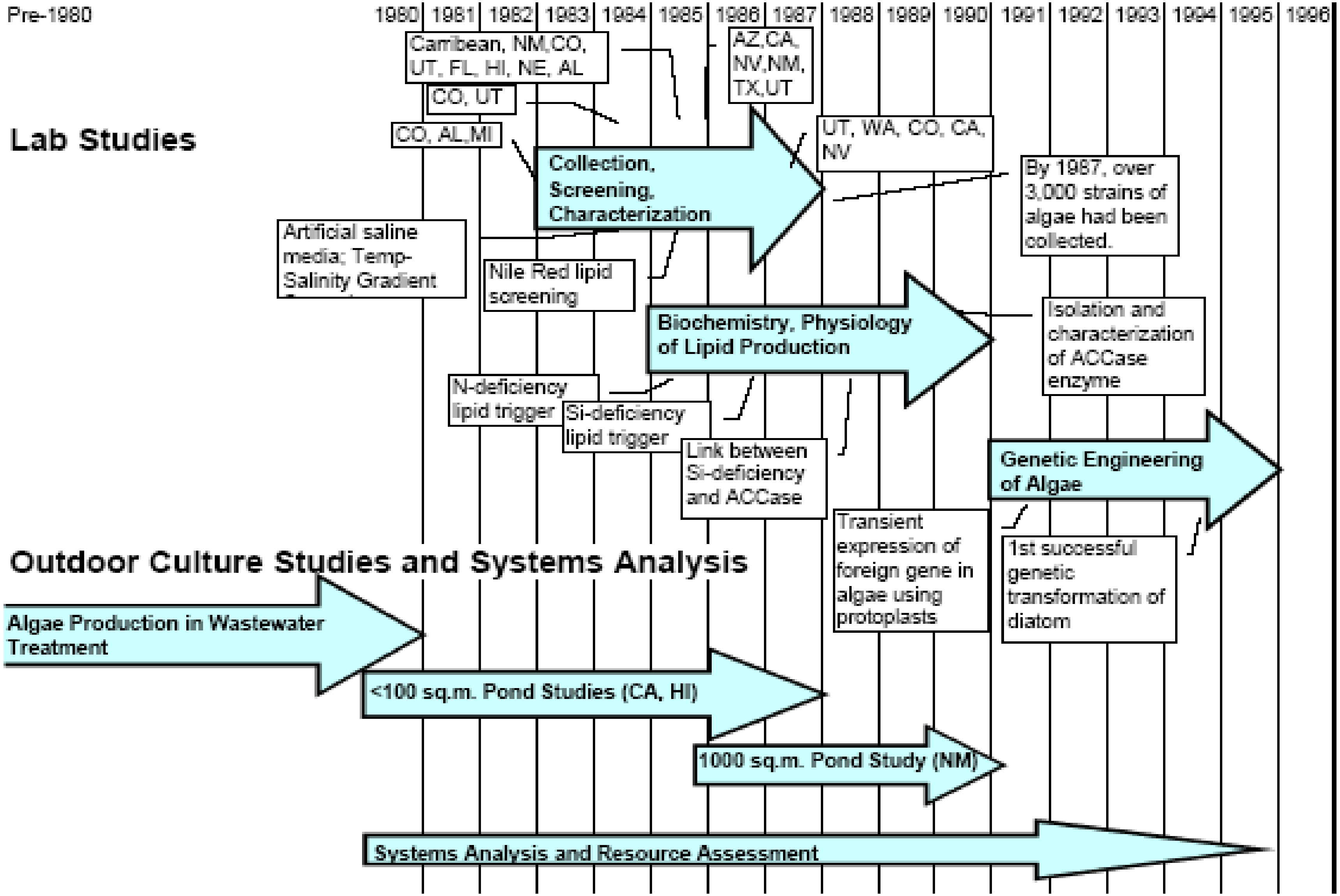


Illustration courtesy NASA Earth Science Enterprise

U.S. CO_2 Emissions

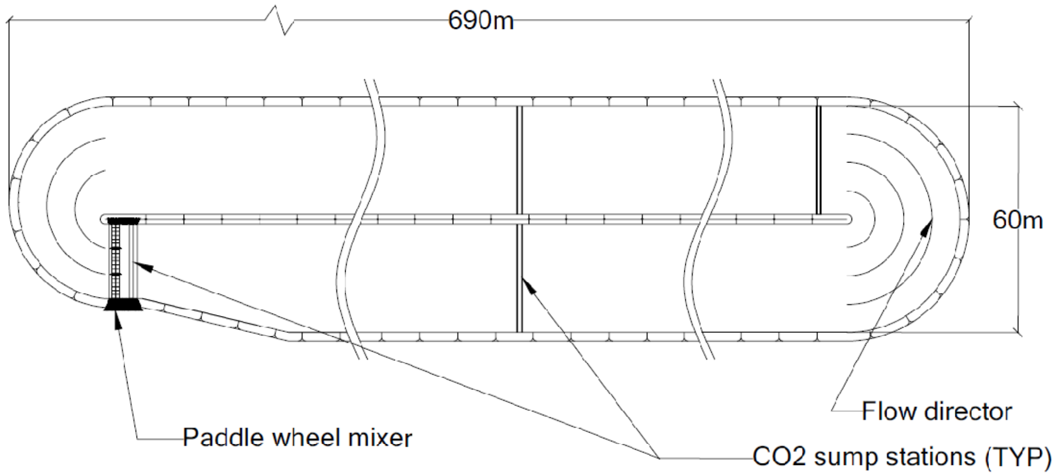
- 6 Gt Fossil fuel use
- ~3 Gt remains in atmosphere
- 1 Gt CO_2 can produce 40 B gallons algal oil
- 1.5 Gt CO_2 could replace the entire yearly petroleum diesel usage in US

Aquatic Species Program



DOE's Aquatic Species Program (ASP)

- **DOE sponsored project (1978-1996)**
- **Goal:** Transportation fuels from algae
- **Focus:** Biodiesel from high lipid algae
- **Accomplishments/Advances:**
  - Applied biology & physiology/design of algae production systems
  - 3,000 strains collected and screened
  - 1,000 m^2 outdoor test facility



Project terminated due to:
- **Decreasing budgets**
- **Focus on cellulosic ethanol**
- **Algal oil ($40-70/bbl) not competitive with petroleum at $20/barrel**

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

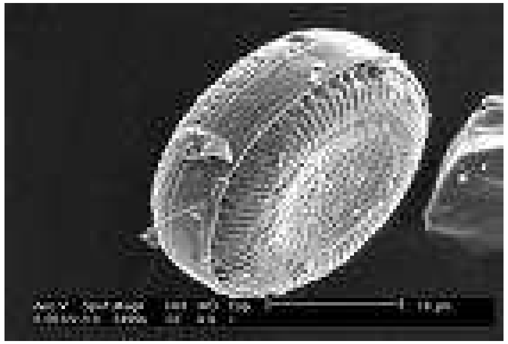


Photo courtesy of the Austin American-Statesman

Physiology, Biochemistry, and Genetic Engineering: Lessons Learned

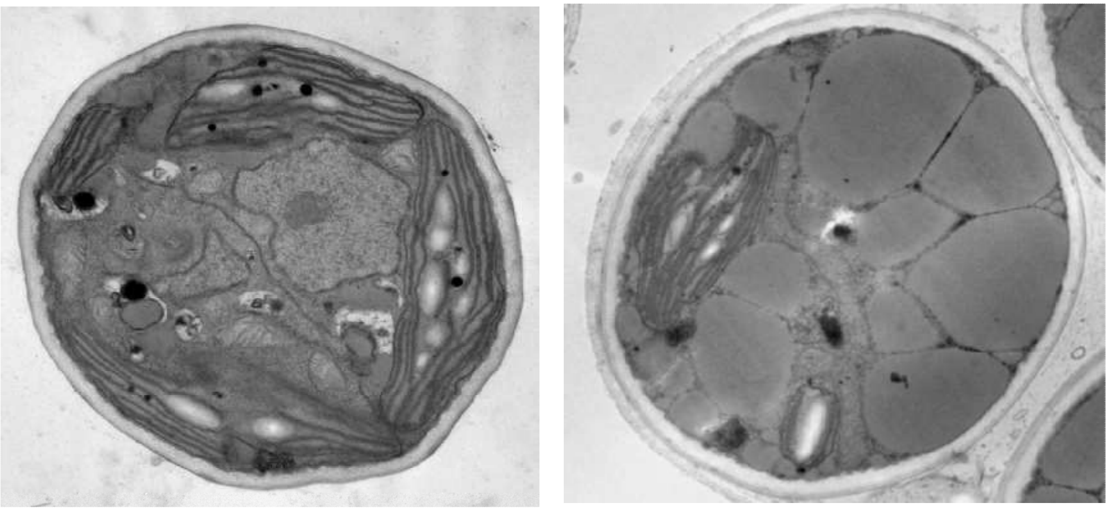
- Lipid induction with nutrient stress doesn't help productivity
- Key enzymes change activity upon induction, but no obvious "lipid trigger"
- We have only begun to scratch the surface
  - Need to understand lipid pathways, regulation, devise genetic strategies

Process Engineering: Lessons Learned

– Flocculation may be most promising route for harvesting/dewatering

– Solvent extraction of oil is feasible; but not economical

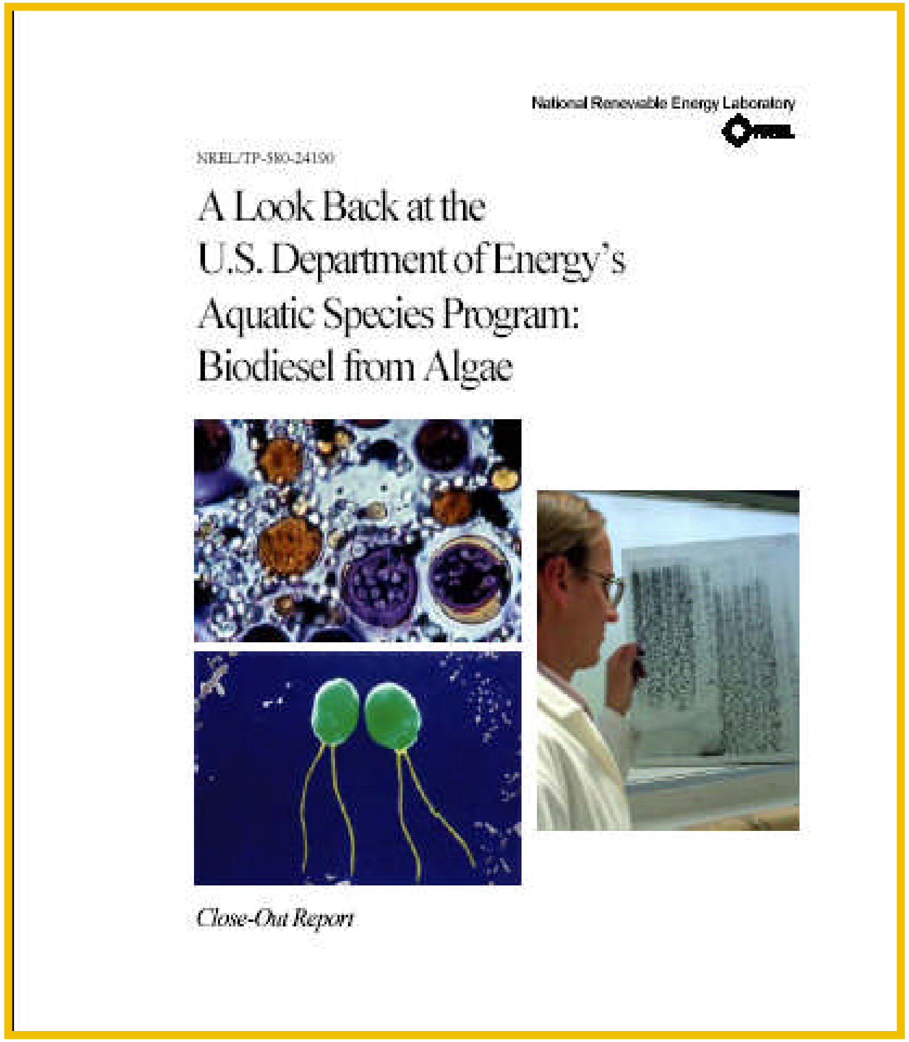
– Development of extraction methods will need a better understanding of cell wall ultra-structure and composition



Photos courtesy: Q. Hu, ASU

ASP Close-Out Report: Future Directions

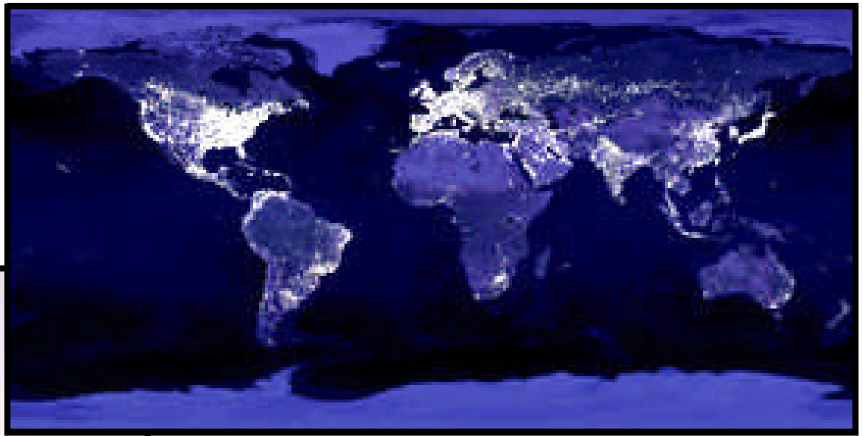
- Less emphasis on field demos; more on basic/applied biology
- Take advantage of plant biotechnology
- Start with what works in the field
- Maximize photosynthetic efficiency
- Set realistic expectations for the technology
- Look for near term technology deployment such as waste water treatment



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

What's Changed Since 1996?

- Record high crude oil prices
- Increasing demand by emerging markets
- Energy security/renewable fuels
- CO_2 capture and GHG reduction
- Explosion in biotechnology
- Industrial entry into the field



GREENFUEL
TECHNOLOGIES CORPORATION

Algae Biofuel Companies

(list growing as quickly as an algal bloom)

A2BE Carbon Capture, LLC
Algae Biofuels
Algae Link
AlgaeWheel
Algenol (ethanol)
Algodyne
Algoil
AlgroSolutions
Aquaflow Bionomic
Aquatic Energy
Aurora BioFuels Inc.
AXI
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 (ethanol)
GS Cleantech
HR Biopetroleum/Shell (Cellana)
IGV
Imperium Renewables
Infinifuel Biodiesel
Inventure Chemical
Kai BioEnergy
KAS
Kent SeaTech Corp.
Kwikpower
LiveFuels, Inc.
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
Texas Clean Fuels
Trident Exploration/Menova
Valcent Products
W2 Energy
XL Renewables

Venture Capital Investments Heating Up

Venture Capital firms invested:

- **$280M Advanced Biofuels (Q1-Q2 2008)**
- **$84M for algae biomass;**
- **$4M invested for algae Q3 2007**

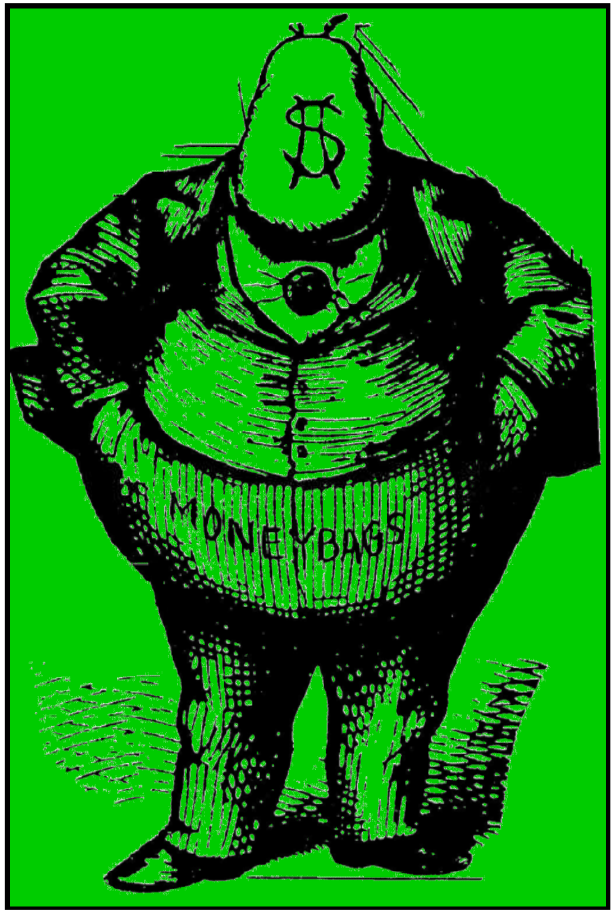
LiveFuels: $10M Series A (2007)

Aurora BioFuels: $20M (2008)

Sapphire Energy: $100M (2008)

Solazyme: $45M (2008)

Algenol Biofuels: $850M investment from Mexico's BioFields; ethanol



Growing Oil Industry Partnerships

Chevron-NREL Alliance: algal oil to transportation fuels (10/07)

Shell-University of Hawaii-HR Biopetroleum: Cellana (JV; 12/07)

ConocoPhillips-C2B2 sponsored research: Biofuels from algae (7/08)

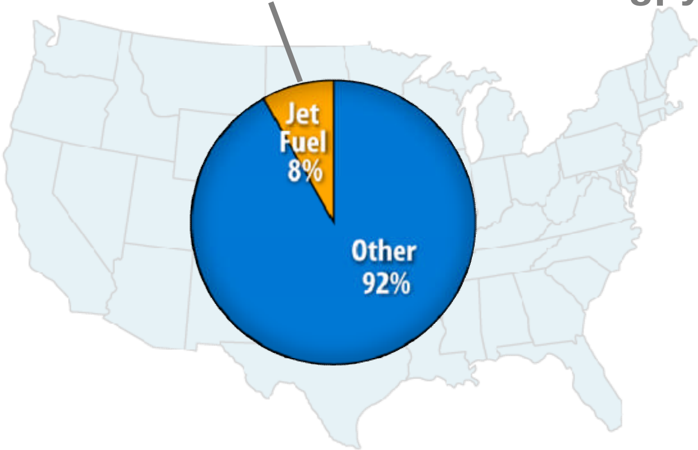
Growing Interest By End Users

- **Pratt & Whitney Canada:** investigating biofuels from algae and jatropha.
- **Boeing:** *“Algae will be 1º feedstock for aviation biofuels within 10-15 years”.*
- **Air France-KLM:** agreement to procure algae oil to be blended with jet fuel.
- **JetBlue, Airbus, Honeywell and the International Aero Engines partnership:** replace 30% of jet fuel with biofuels from algae and other non-food vegetable oils.
- **Air New Zealand:** jatropha as a fuel

Growing Federal Interest

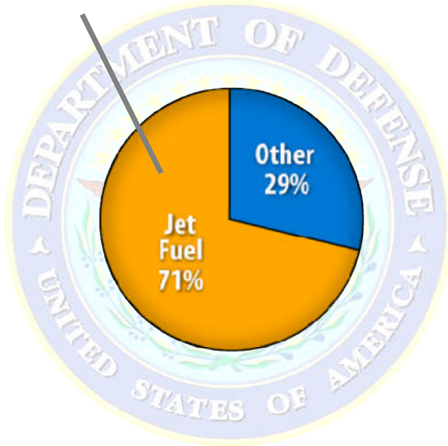
Commercial US Fuel Consumption

(US Airline Jet Fuel Demand ~ 20 B gpy)

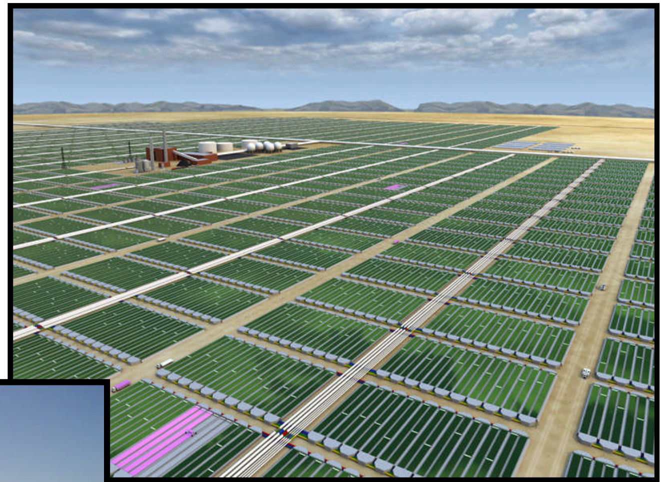


DOD Fuel Consumption

DOD's Total Jet Fuel Demand ~ 5 B gpy



No shortage of cultivation ideas…



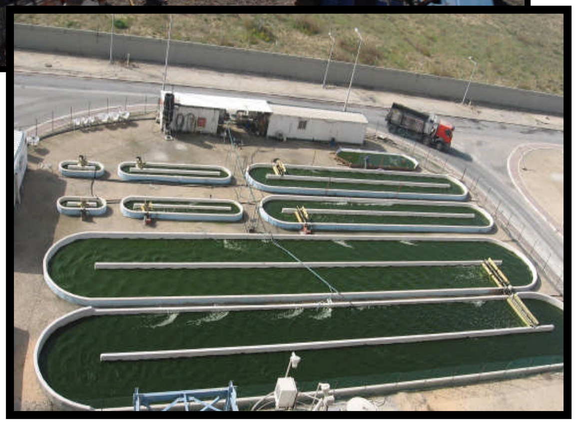


Image courtesy: A. Ben-Amotz, Seambiotic

Microalgae Hype vs. Reality

So why microalgae?…………..*Reality Check*

• **Grow faster**	***Not all that relevant (except for R&D)***
• **More productive**	***Likely, but not proven (R&D)***
• **Use power plant flue gas CO_2**	***A need, not a virtue***
• **Have high oil content**	***OK, but must be productive***
• **Use saline, brackish, waste waters**	***Yes, but use less water***
• **Not compete with agriculture**	***Yes, but we can eat algae***
• **Low cost of production/processing**	***Not true!***
• **Very large production potential**	***Many limitations***
• **Co-products, nutrient recycle, waste treatment**	***YES!***

J. Benemann, 5th Annual World Congress on Industrial Biotechnology, Chicago, April 30, 2008

Algae System Parameter Comparison

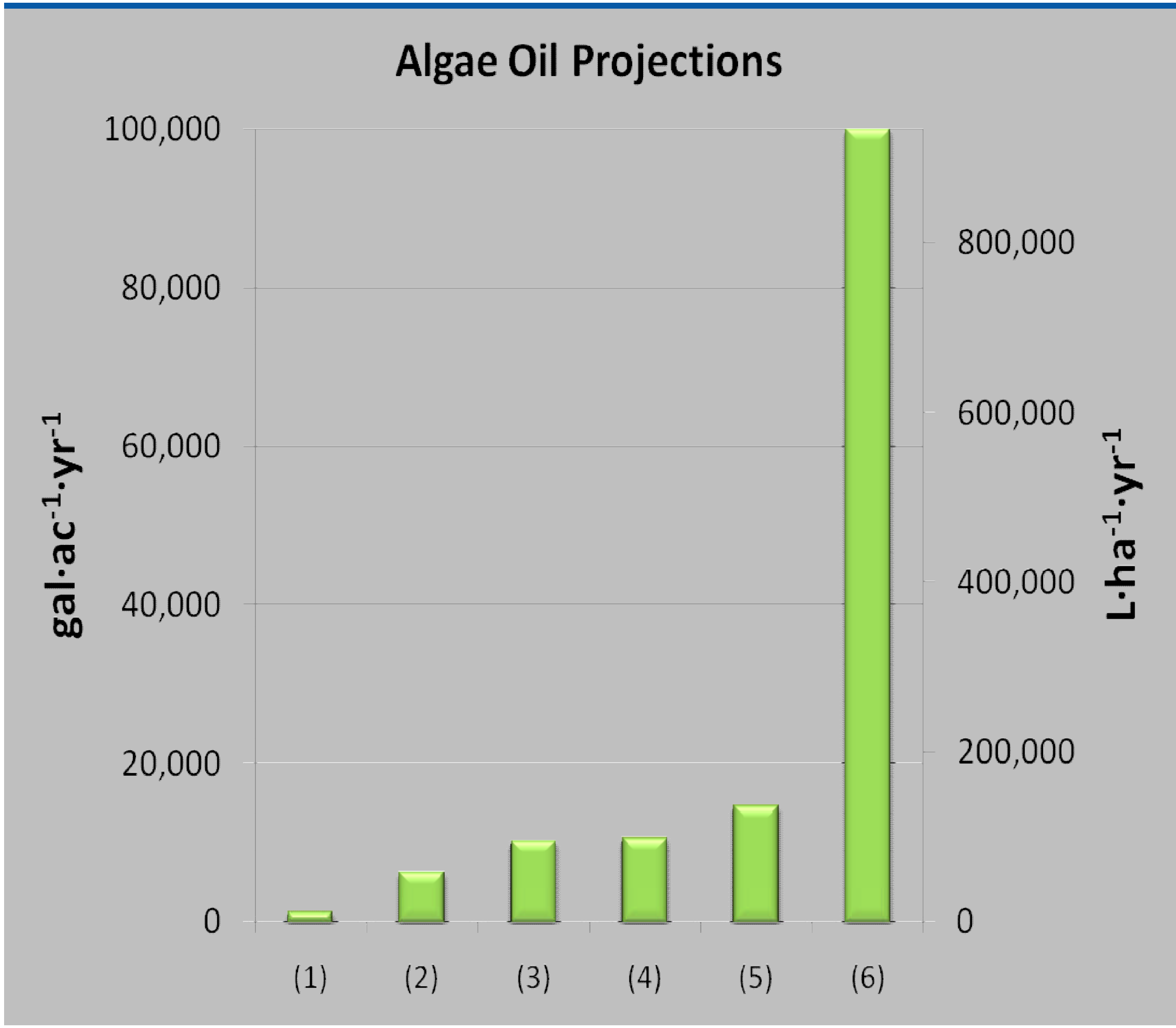
Open ponds vs *closed photobioreactors*

Parameter	Relative Advantage	Notes
Contamination risk	Ponds < PBRs	Just a matter of time
Productivity	Ponds ~ PBRs	No substantial difference
Space required	Ponds ~ PBRs	A matter of productivity
Water losses	Ponds ~ PBRs	Evaporative cooling
O_2 inhibition	Ponds > PBRs	O_2 major problem in PBRs
Process control	Ponds ~ PBRs	No major differences
Capital/operating	Ponds << PBRs	Ponds have lower costs

Conclusions: Biofuels can't afford PBRs; inoculum production?

J. Benemann, 5th Annual World Congress on Industrial Biotechnology, Chicago, April 30, 2008

Theoretical Maximum Algal Oil Production



(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

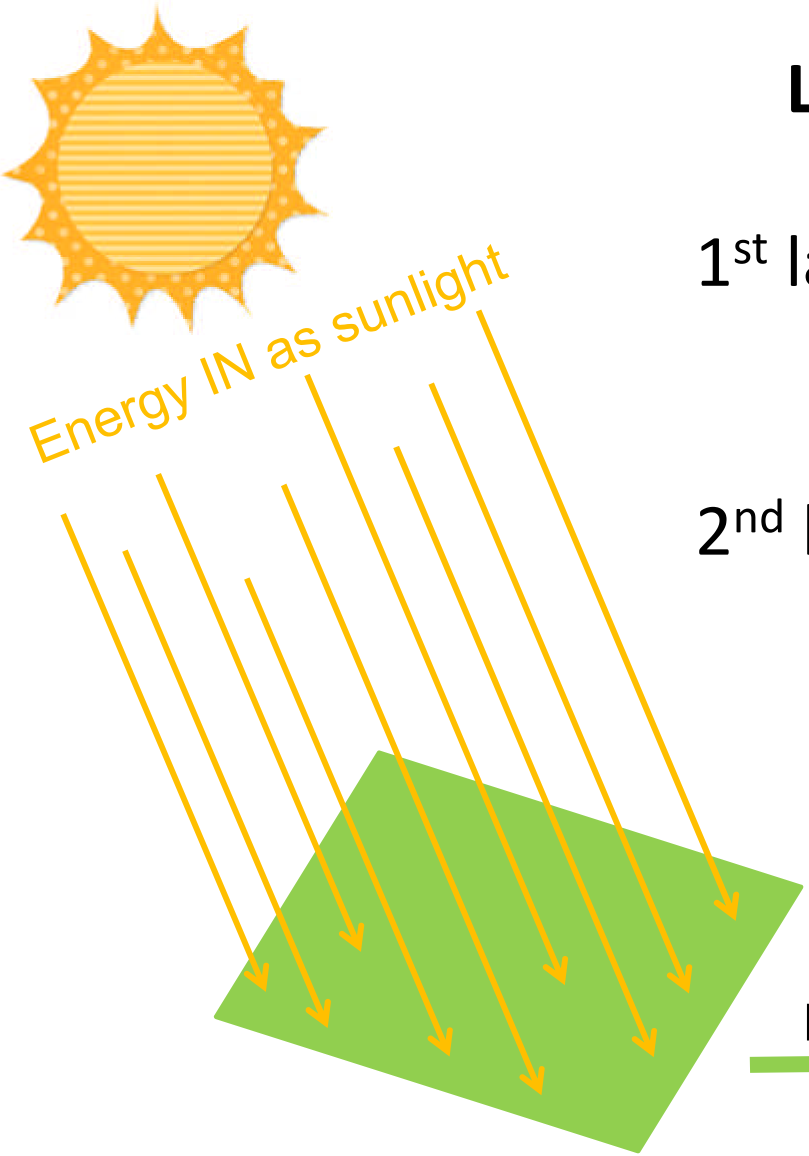
Wide range of projections…

Hype vs. reality

What is the ultimate upper limit?

Source: Kristina Weyer, Solix Biofuels

Method



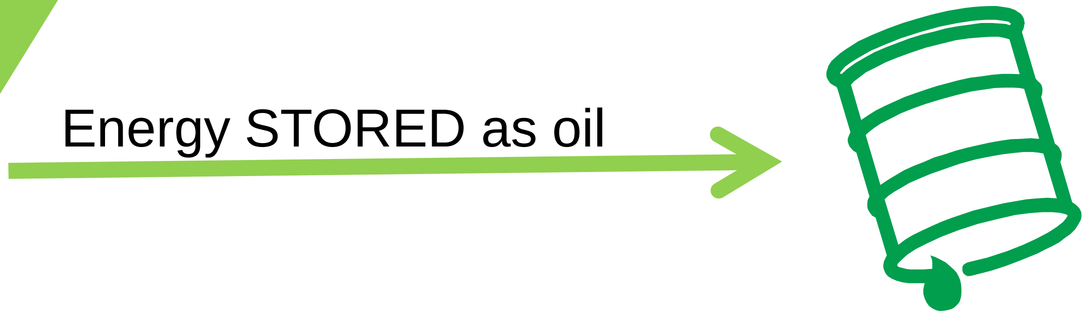
Laws of Thermodynamics

1st law: conservation of energy

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

2nd law: 100% efficiency is not possible

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



Source: Kristina Weyer, Solix Biofuels

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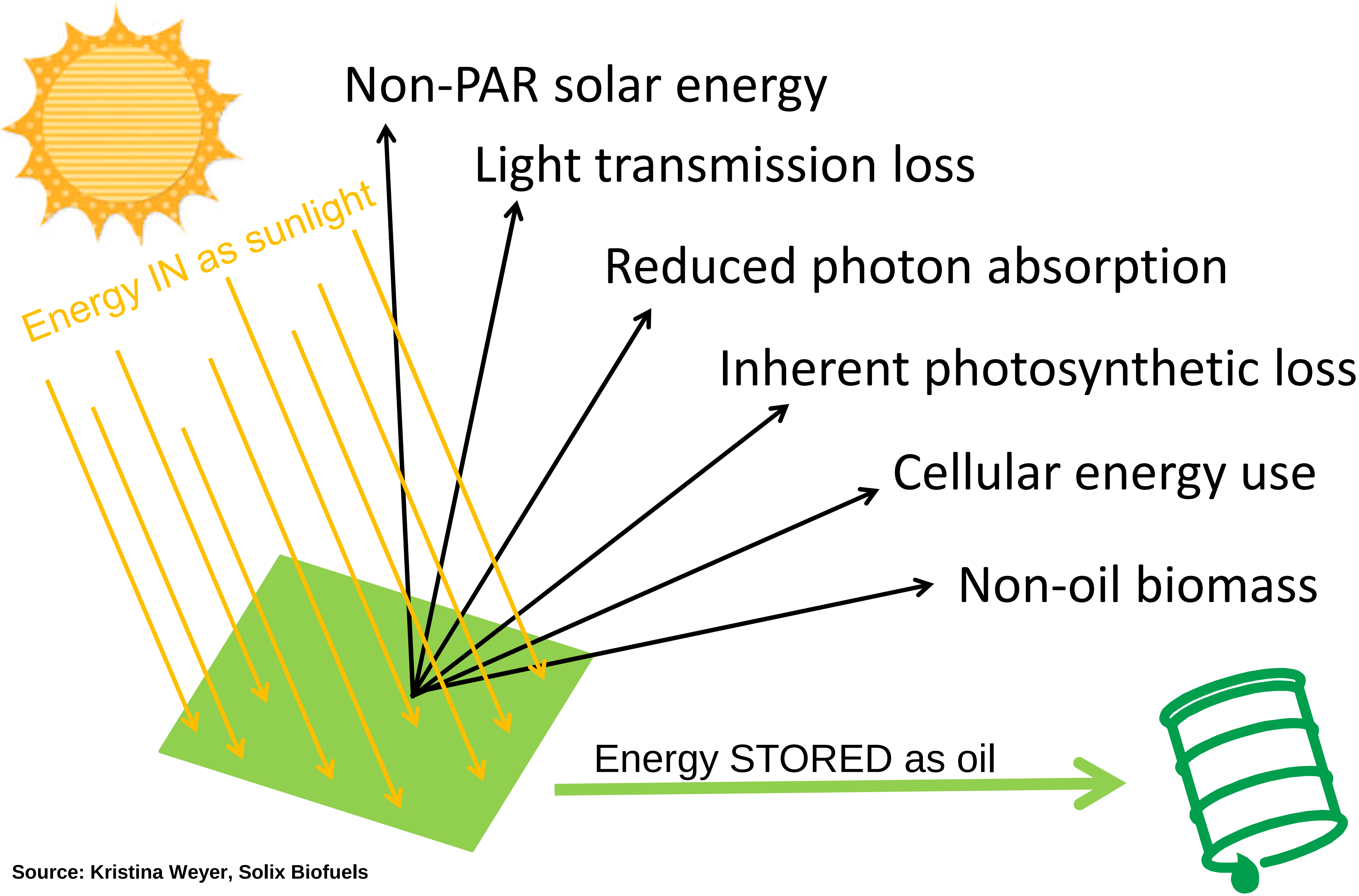


Source: Kristina Weyer, Solix Biofuels

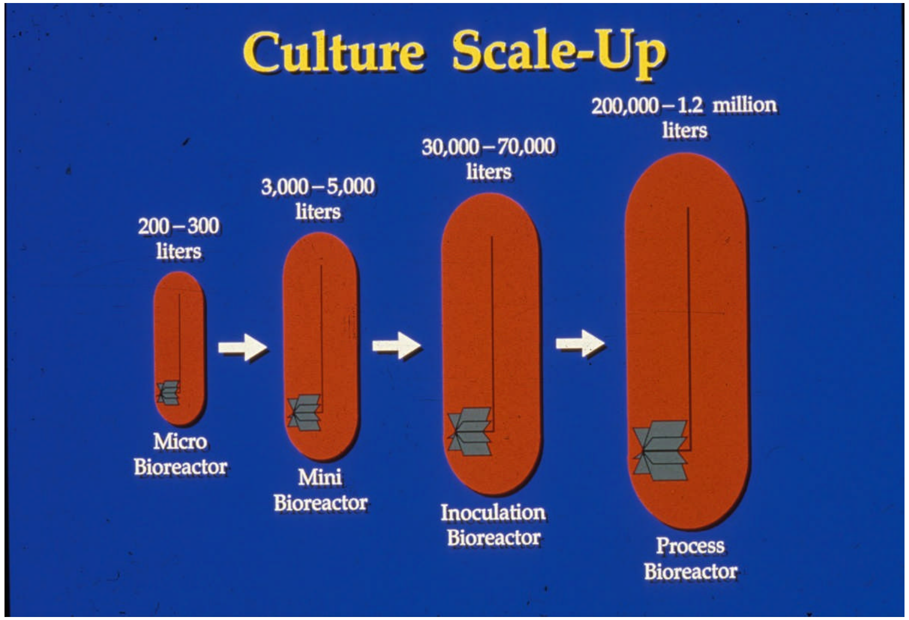
Down Stream Processing Issues

A Major Challenge: Harvesting Algal Biomass

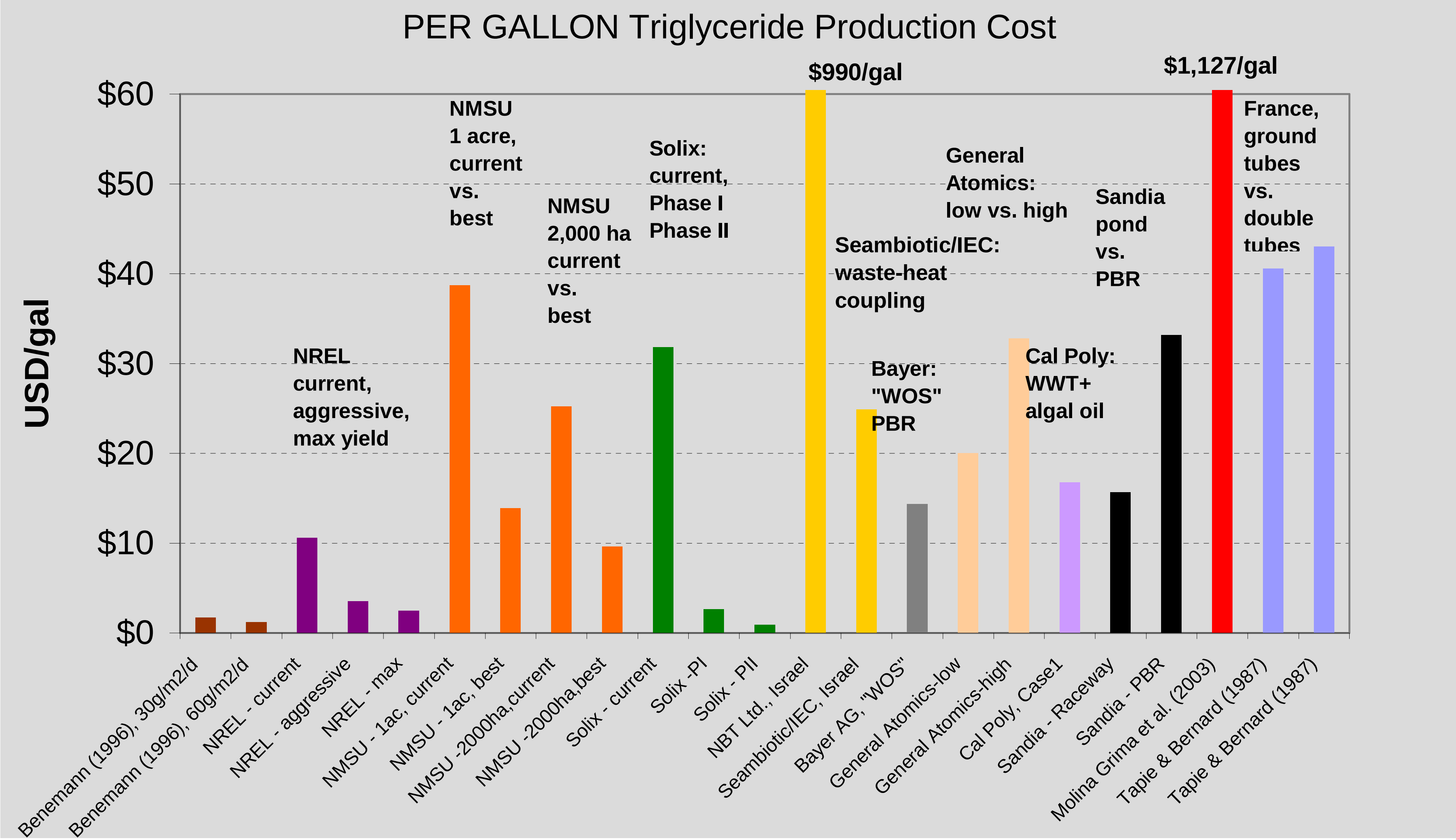
- Microalgae are microscopic - 10μM
- Need to harvest 30% of the culture every single day
- Concentration in ponds at harvest only 400mg/liter
- Harvesting means conc. 500-fold (for 20% solids)
- First 100-fold most difficult (use centrifuge afterwards)
- Must cost <$50/ton
- Chemical flocculation is too expensive
- Only likely way: spontaneous settling (bioflocculation)

Scale-up Issues

- Large scale production will need to occur in engineered open ponds
- Site selection is critical for microalgae cultivation
- Species selection must be tailored to the site conditions and product
- Real scale-up issues will arise when you try to design and operate a fully integrated production system



Standardized Cost Comparison



- *Average = $109 USD/gal*
- *Variability is wide, Std. Dev. = $301 USD/gal*

Source: NREL and Sandia

Objectives:

- **Convene a national algae workshop (Dec. 9-10, 2008)**
- **Identify key technical hurdles that hinder cost-effective production of algal-based biofuels**
- **Draft comprehensive algal biofuels roadmap (April 09)**
- **Recommend research strategies to address the barriers**

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).

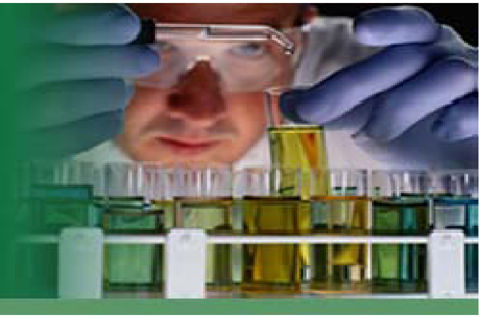
Undemanding of Fresh Water: Many species of algae thrive in seawater, water from saline aquifers, or even wastewater from treatment plants.

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.

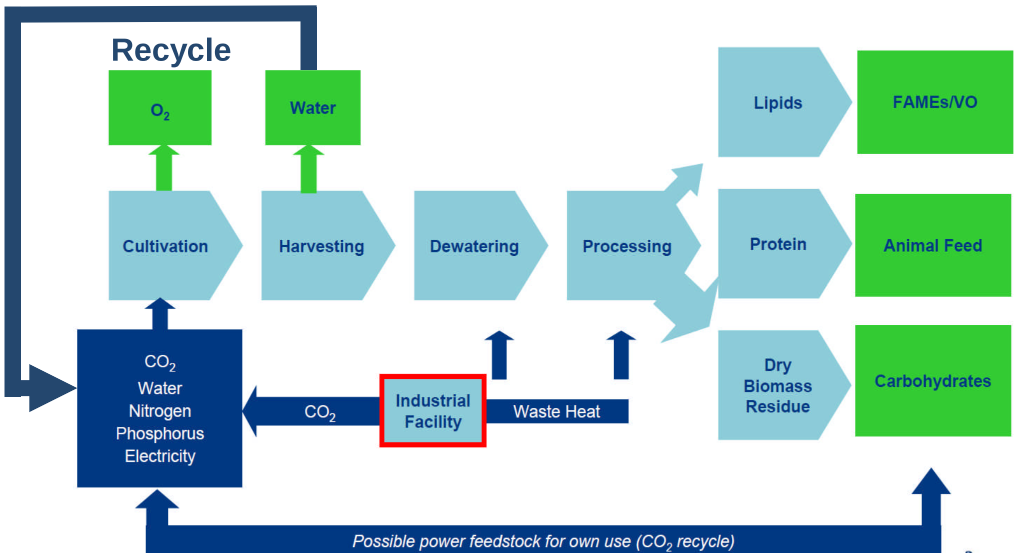
Broad Product Portfolio: The lipids produced by algae can be used to produce a range of biofuels, and the remaining biomass residue has a variety of useful applications:

- 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:



- Algal Biology
- Cultivation
- Harvest/dewatering
- Extraction/fractionation
- Conversion to fuels
- Co–products
- Systems integration
- Siting & Resources
- Regulation & Policy

Re-establishment of NREL's Algal Biofuels Program

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) Energy Secretary to present to Congress a report on the feasibility of <u>microalgae</u> as a feedstock for biofuels production**

DOE-Israel Collaboration

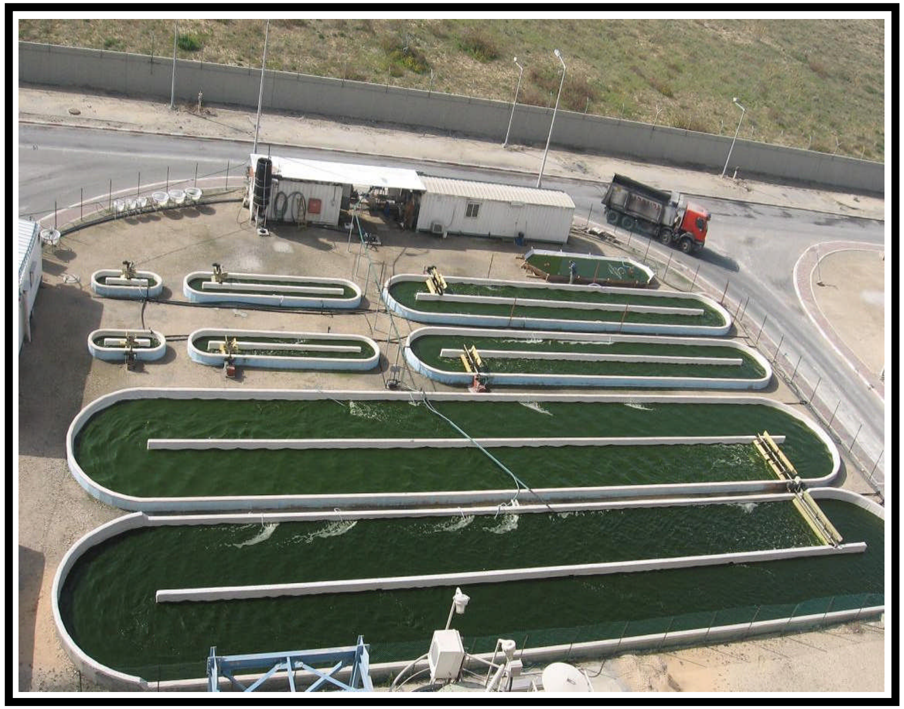
Development of Novel Microalgal Production and Downstream Processing Technologies for Alternative Biofuels Applications

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



Ashkelon, Israel

Image courtesy: A. Ben-Amotz, Seambiotic

Chevron Algae CRADA

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

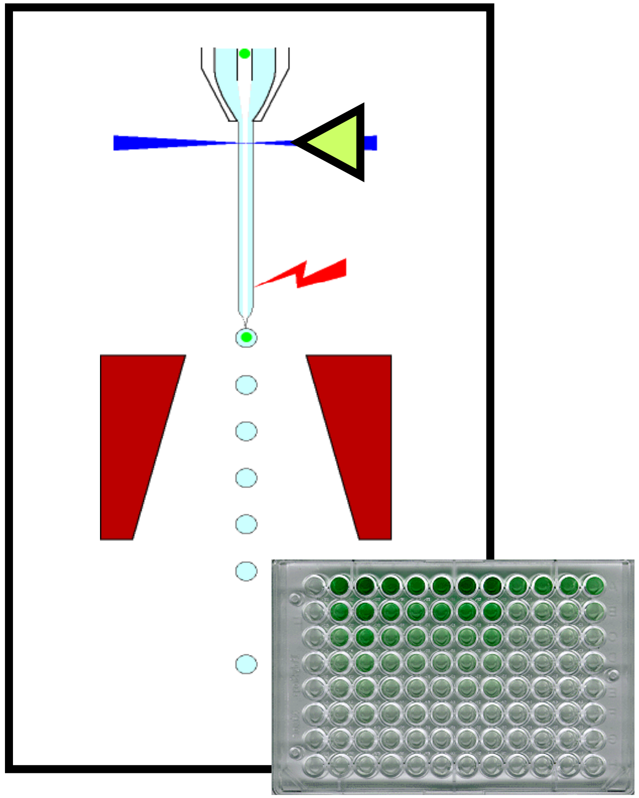
Goal: Identify and develop algae strains that can be economically harvested and processed into finished transportation fuels

Strategic Equipment Acquisitions

NREL General Purpose Equipment (GPE)

Fluorescence Activated Cell Sorter (FACS)

Custom BD FACS*Aria*

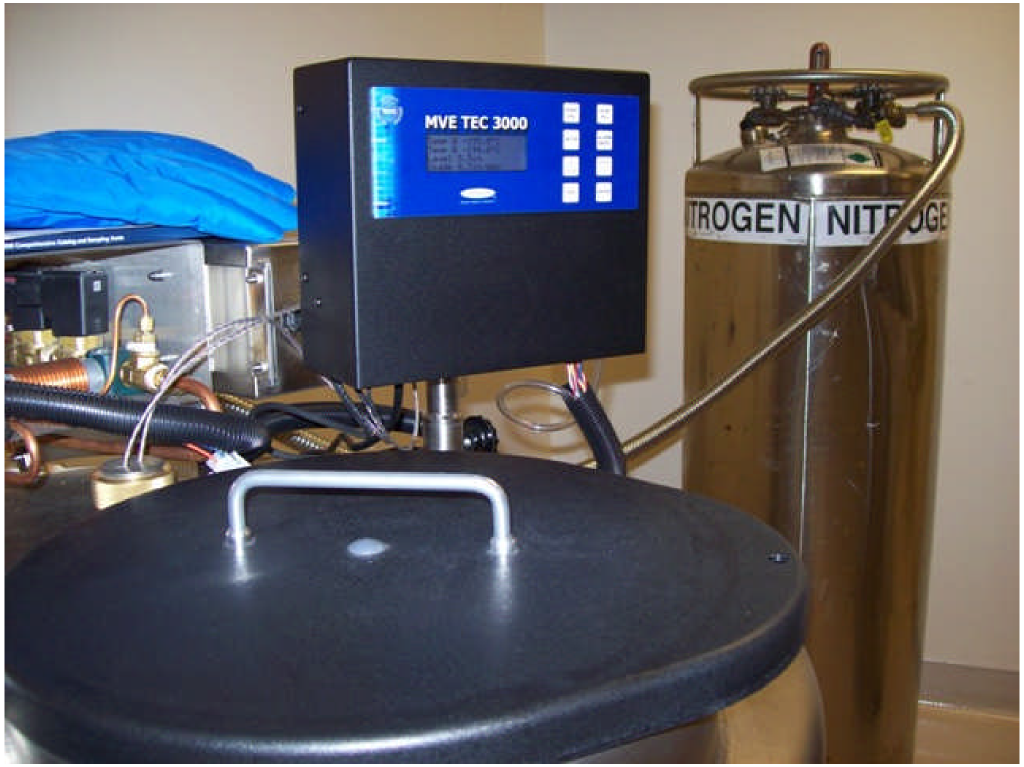


Capability: High-speed algal cell sorting (populations and individual cells)

Strategic Equipment Acquisitions

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 600 sq ft algal lab

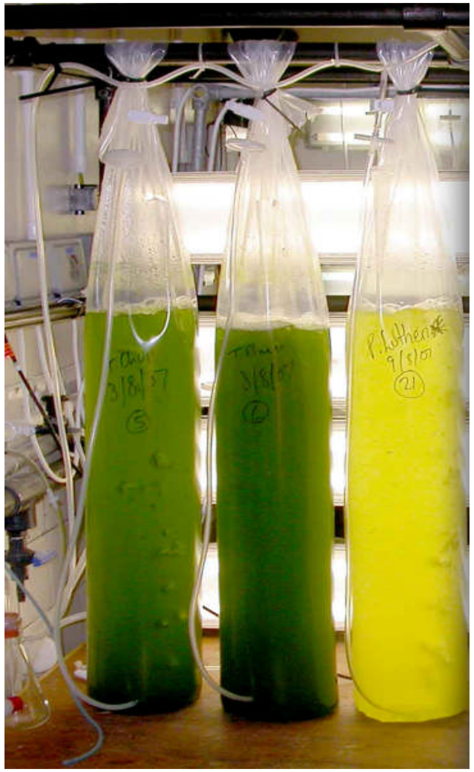


Image courtesy: Lieve Laurens, NREL

Facilities: Large-scale algae cultivation

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

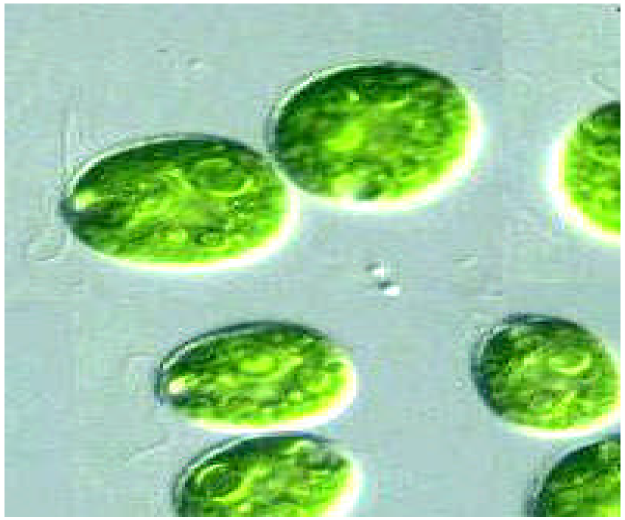
Warren Tech H.S. (10,000 sq. ft greenhouse space)

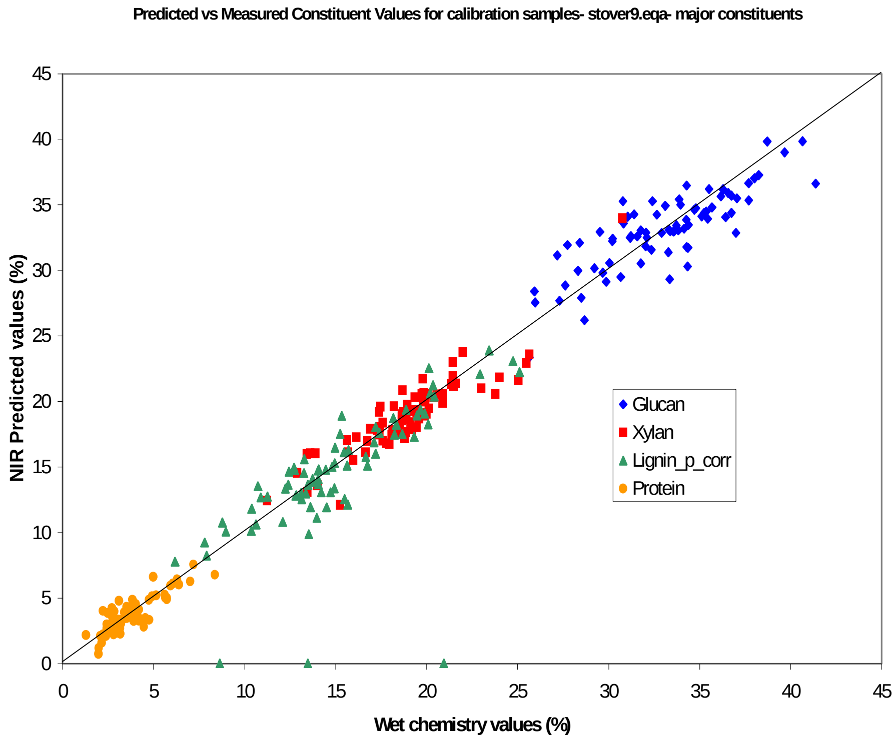
NREL LDRD Project #1

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



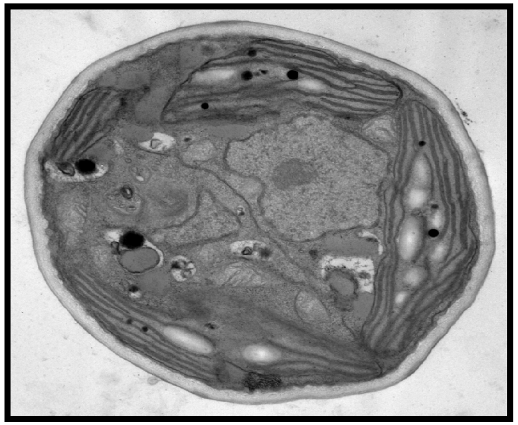


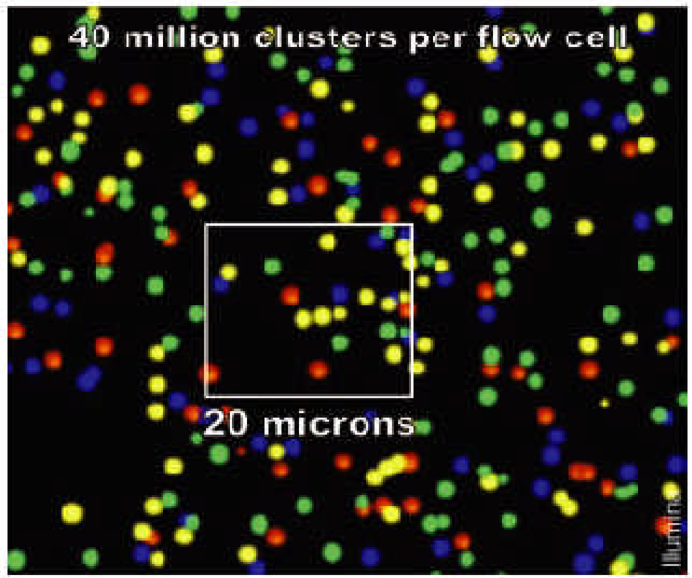
NREL LDRD Project #2

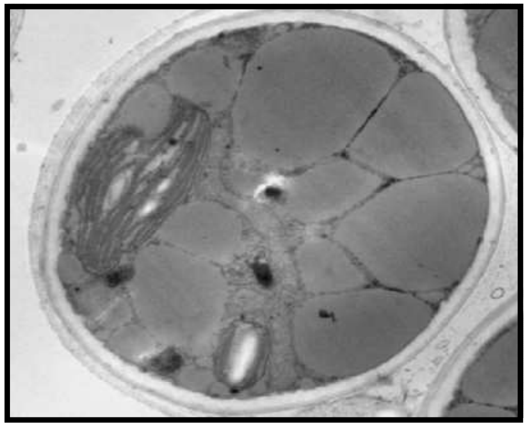
Laboratory Directed Research & Development (LDRD) Award

"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







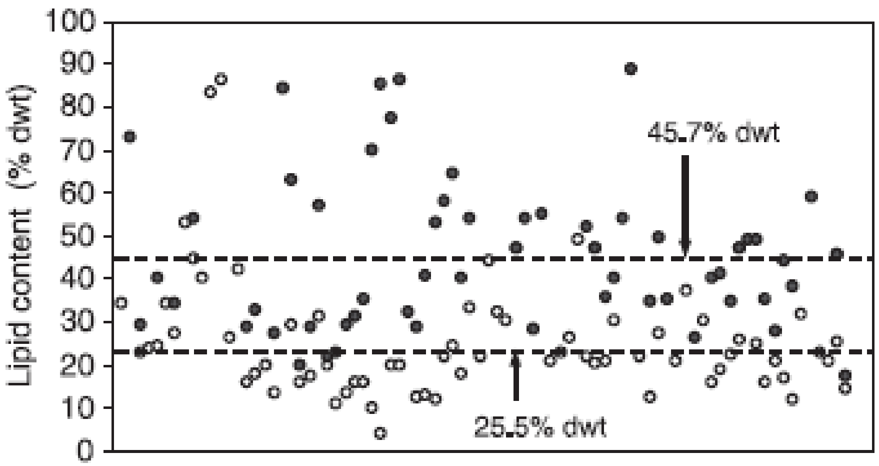
Photos courtesy: Q. Hu, ASU

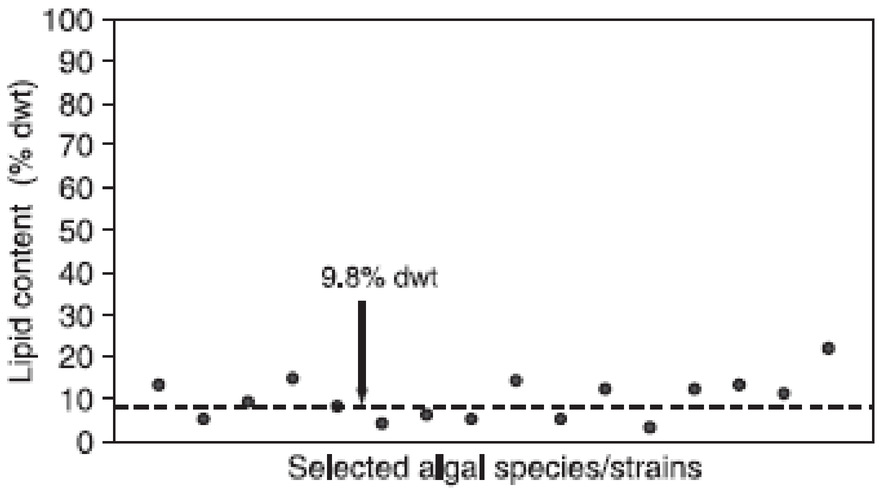
NREL LDRD Project #3

Laboratory Directed Research & Development (LDRD) Award

"Biodiesel from *Cyanobacteria*"

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





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.

C2B2 Seed Grant Project

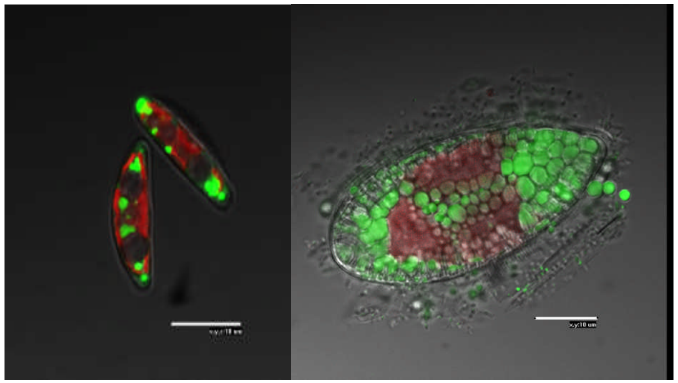
Colorado Center for Biorefining and Biofuels (C2B2) 2007/2008 Seed Grant Award

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

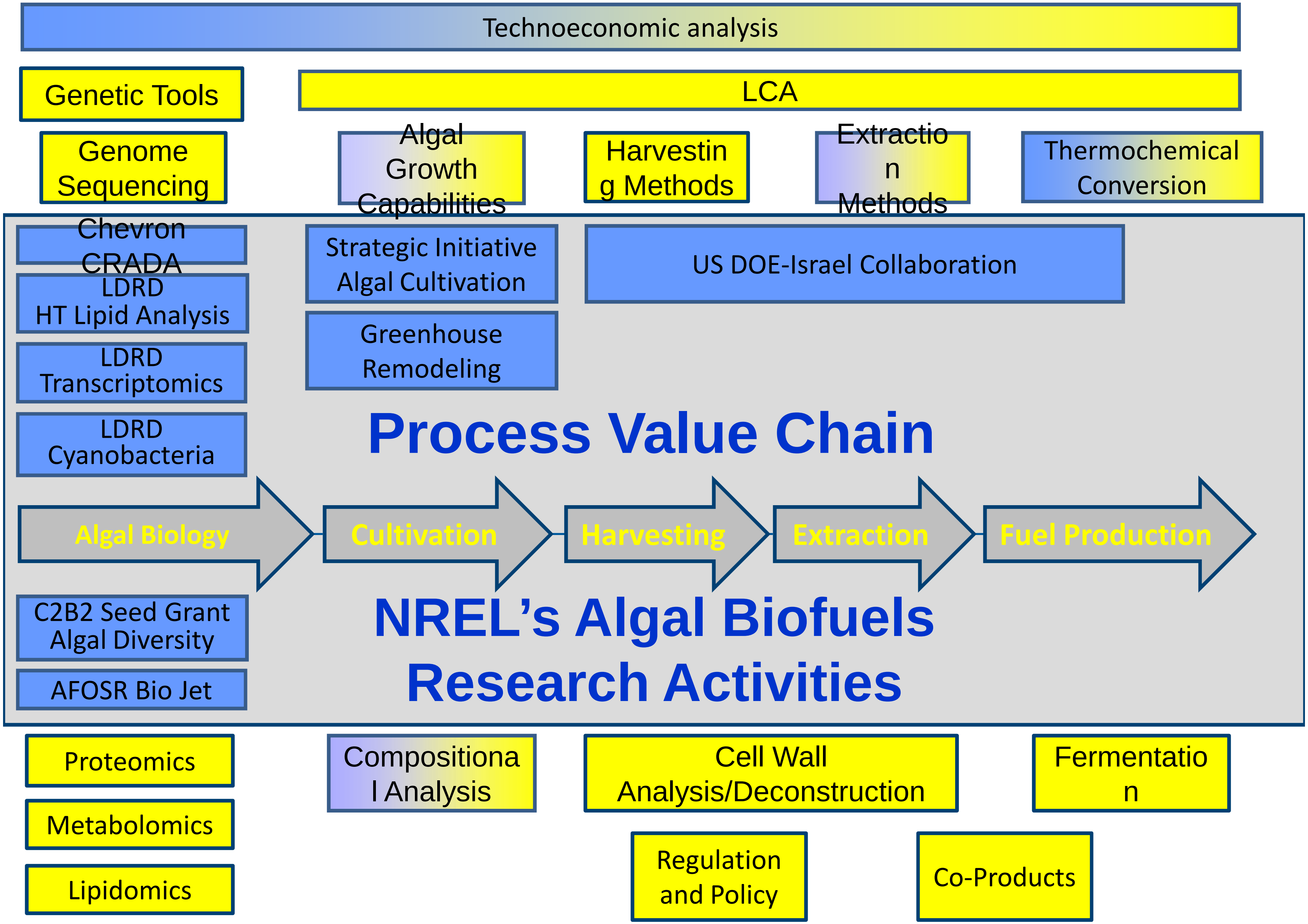
P.I., A. Darzins; co-PI, M. Posewitz; L. Elliott; R. Sestric

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


Technoeconomic analysis
Genetic Tools
LCA
Genome Sequencing
Algal Growth Capabilities
Harvesting Methods
Extraction Methods
Thermochemical Conversion
Chevron CRADA
Strategic Initiative Algal Cultivation
US DOE-Israel Collaboration
LDRD HT Lipid Analysis
LDRD Transcriptomics
Greenhouse Remodeling
LDRD Cyanobacteria
Process 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

Conclusions

- Production of lipid-based fuels from algae have been demonstrated.
- Algae can be grown, harvested; lipids extracted and converted to transportation fuels
- Algal biofuels are possible; can it be made economically and at a scale to help contribute to U.S. fuel demand?
- The potential of algal biofuels is significant
- Greater understanding of the underlying principles is necessary before commercial scale-up is feasible.
- Biological & engineering considerations are critical; fundamental/applied R&D will be needed.
- Needs coordinated support from relevant government agencies, private sector, academia, and stakeholders.

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John Jechura

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- DOE-EERE OBP


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