National Renewable Energy Laboratory
Innovation for Our Energy Future

Algal Biofuel Technologies

States Biomass/ Clean Cities Web Conference

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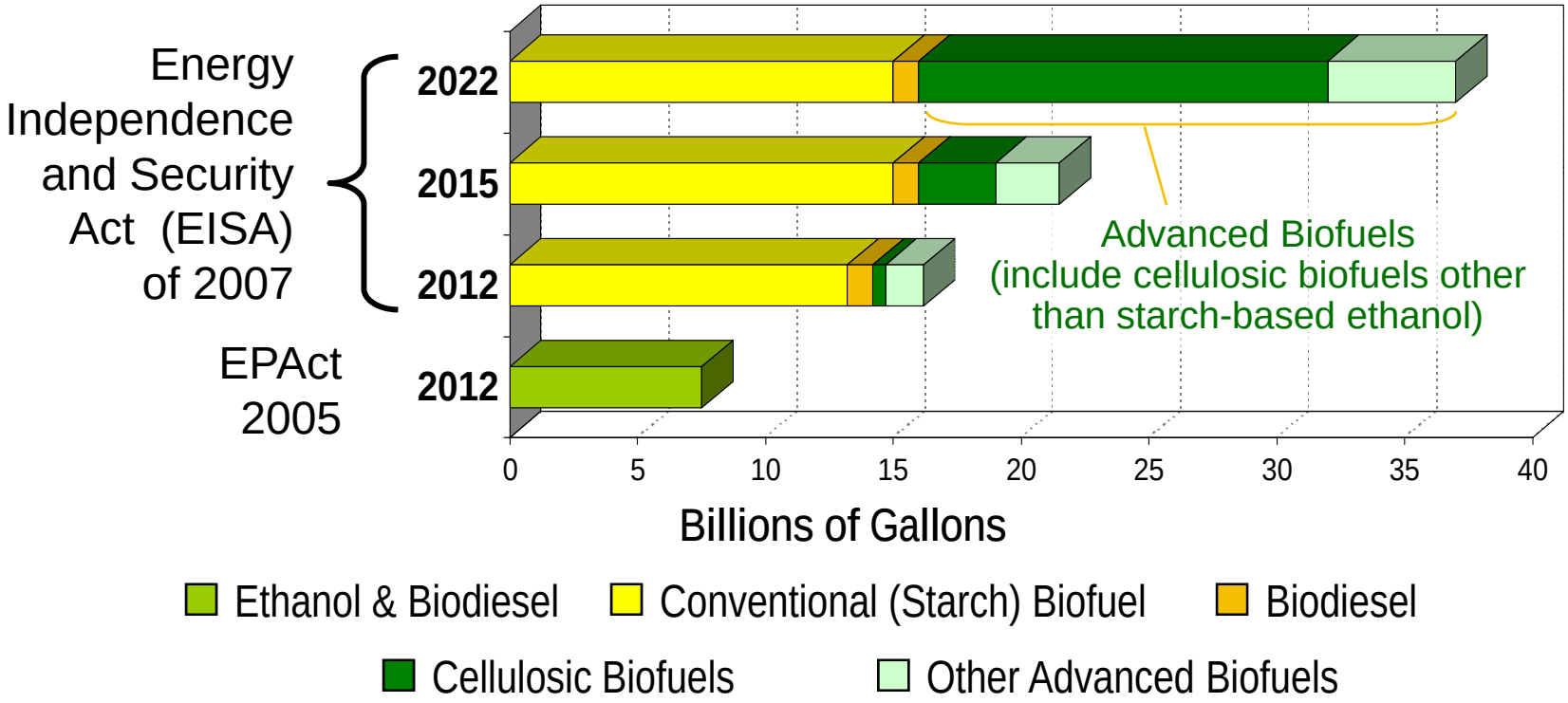
Advanced Biofuels in 2007 EISA

Section 202 – Renewable Fuels Standard sets aggressive volumetric goals:

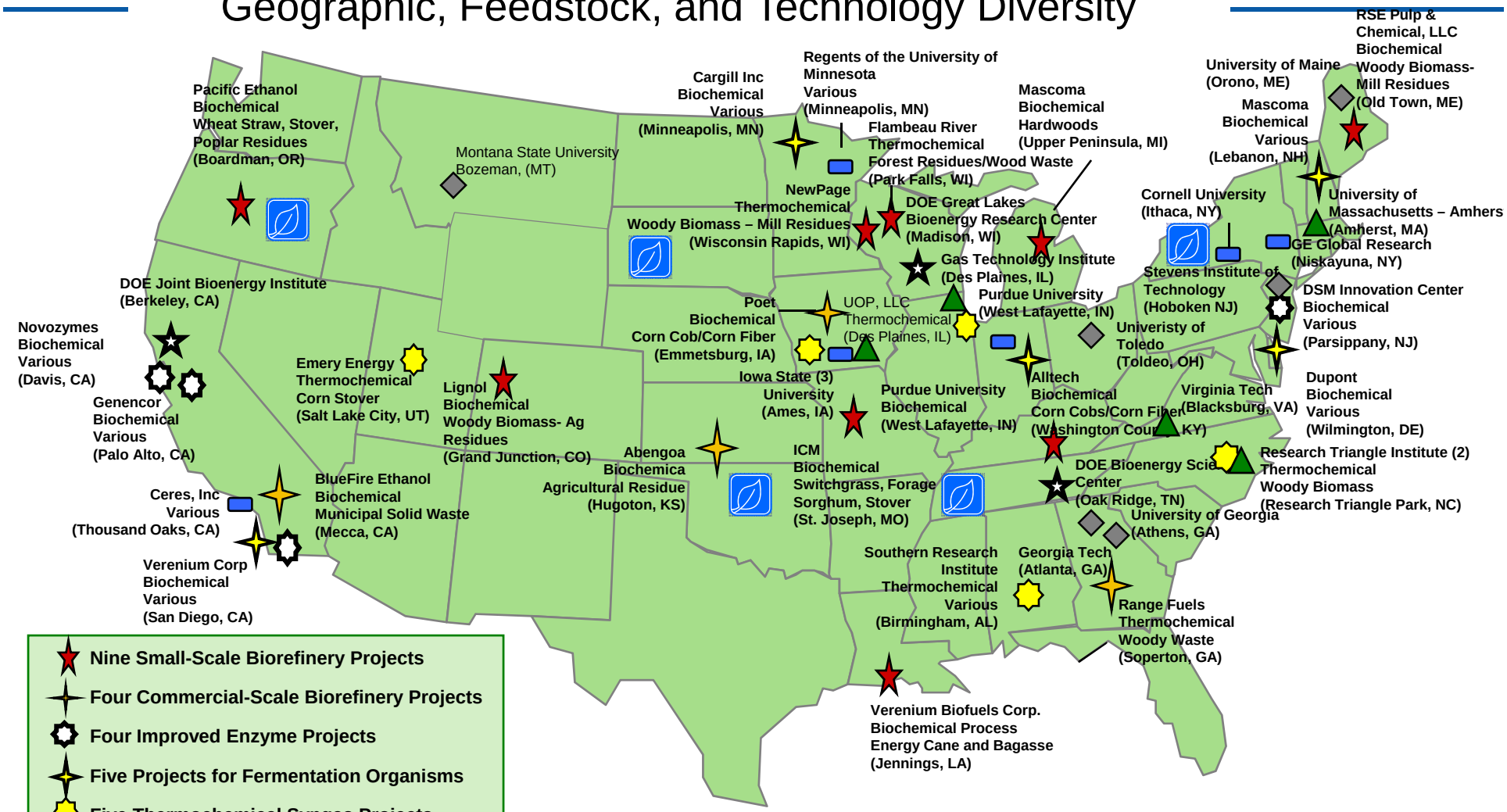
2009	600 million
2010	950 million
2011	1.35 billion
2022	21 billion

To meet these goals, development **must** move beyond biodiesel and ethanol to fuels 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



Regional Partnerships
South Dakota State Univ., Brookings, SD
Cornell University, Ithaca, NY
Univ. of Tennessee, Knoxville, TN
Oklahoma State Univ., Stillwater, OK
Oregon State Univ., Corvallis, OR

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

Advanced Biofuel Options

- Recent studies highlight the potential of advanced biofuels other than cellulosic ethanol.
- Compared to ethanol, next generation biofuels will be more similar in chemical makeup to gasoline and diesel fuels.
- Compatibility with the existing infrastructure may expedite rapid displacement of petroleum (hydrocarbon-based fuels) in the market.

Green gasoline
Cellulosic biobutanol
Algal-based biodiesel/green diesel

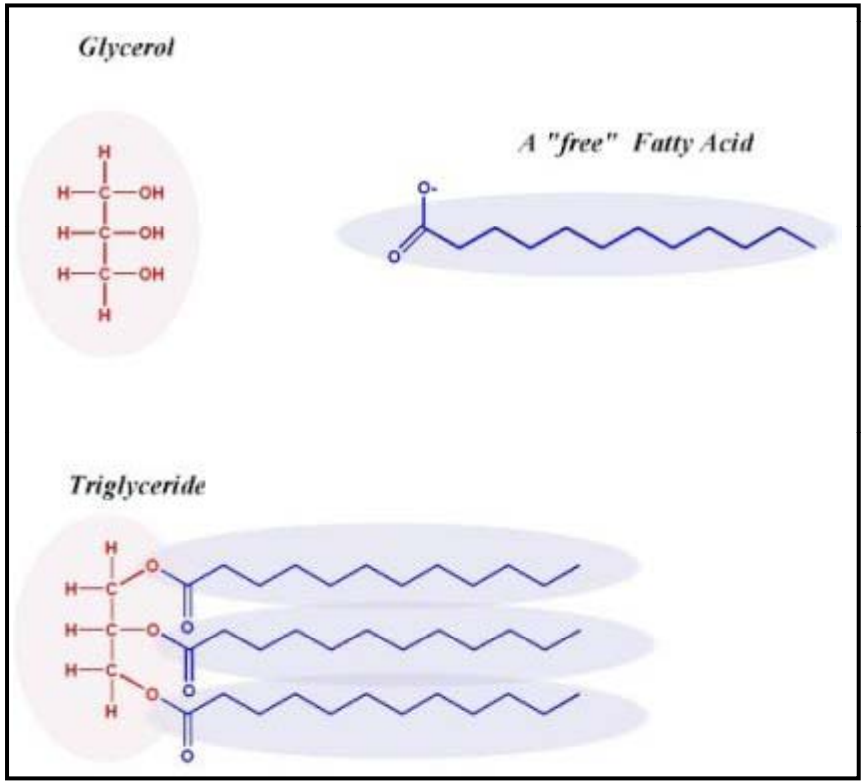
} **Hydrocarbon-Compatible (Infrastructure-Compatible) Advanced Biofuels**

The Biodiesel Dilemma

Triglycerides (TAGs) from oilseed crops can't come close to meeting U.S. diesel demand (60+ billion gal/yr)

U.S. soy oil: 3 B gallons per year

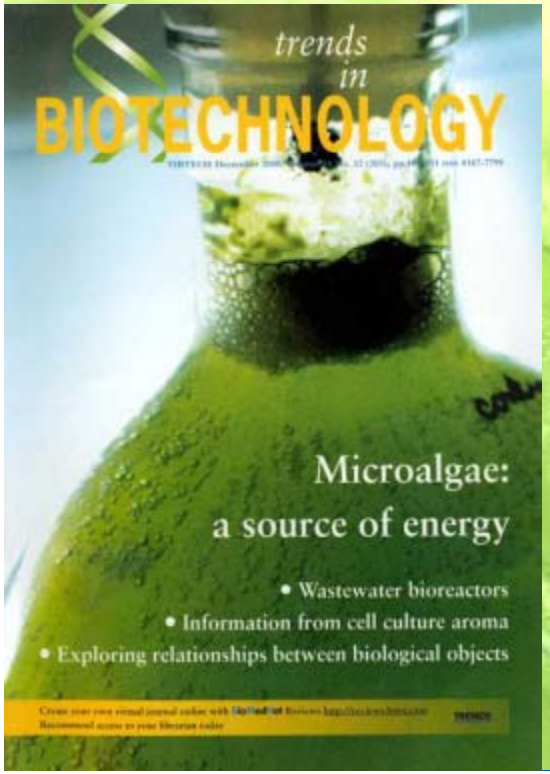
- Conversion to biodiesel replaces only 5% of petroleum diesel usage
- This agricultural productivity can't be diverted from the food supply.
- Cost of feedstock increasing
- Input costs high – must compete with high valued food market

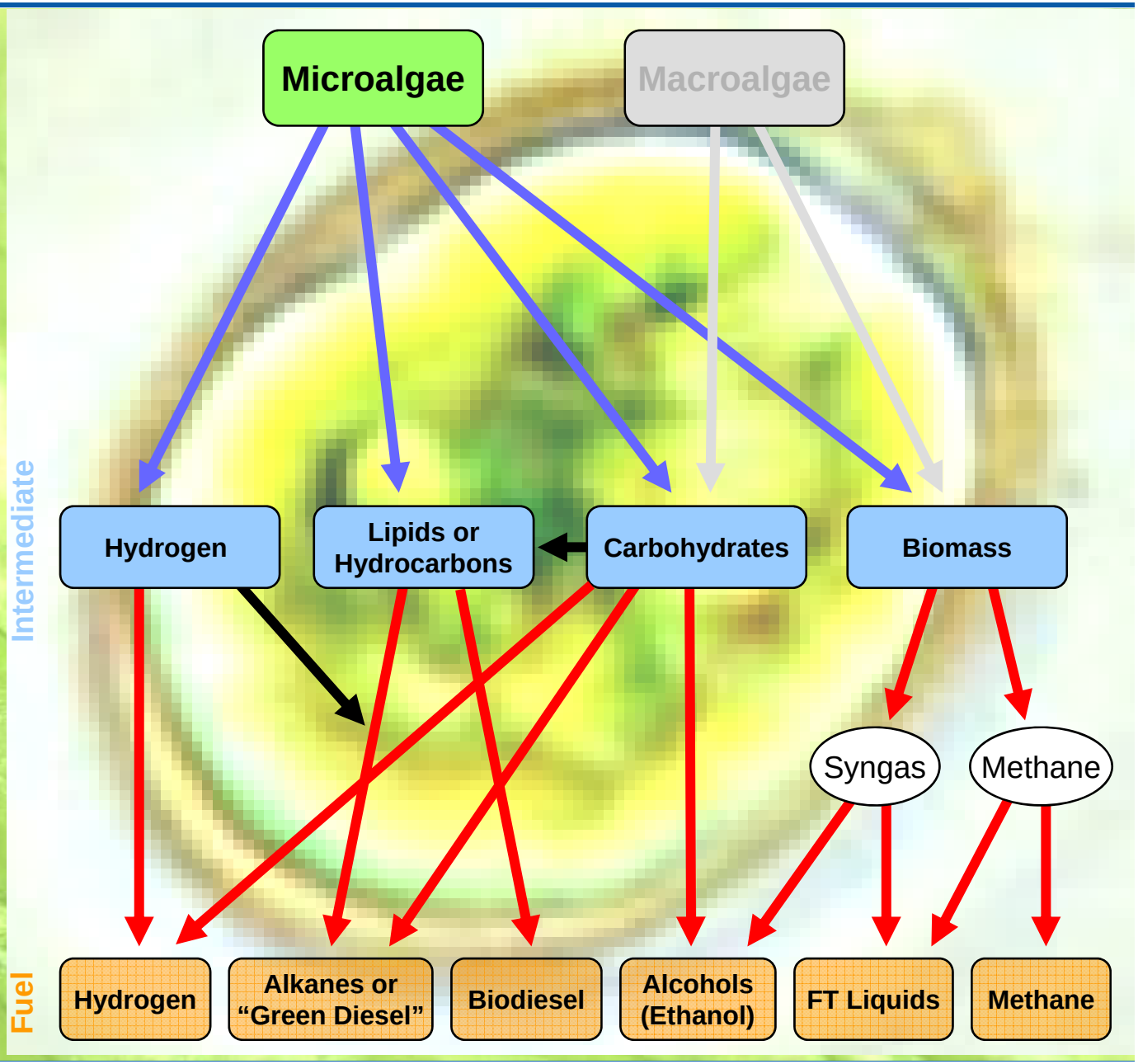


Alternative sources of TAGs are needed!

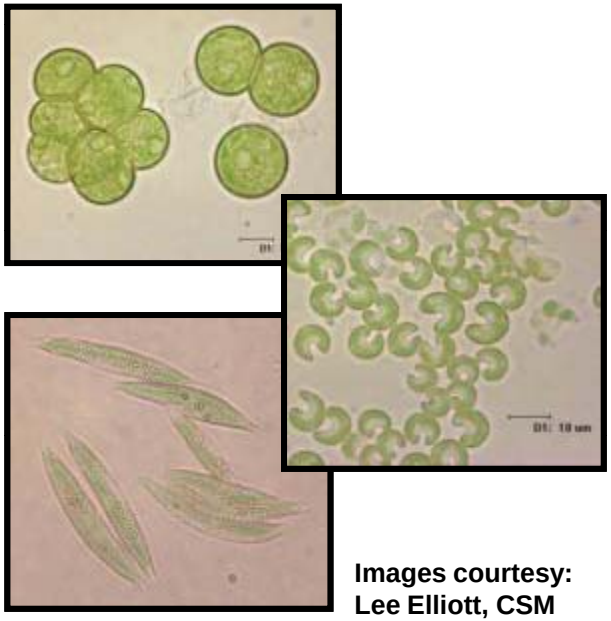
Algae: Numerous Bioenergy Routes

Defining a Biofuels Portfolio From Microalgae

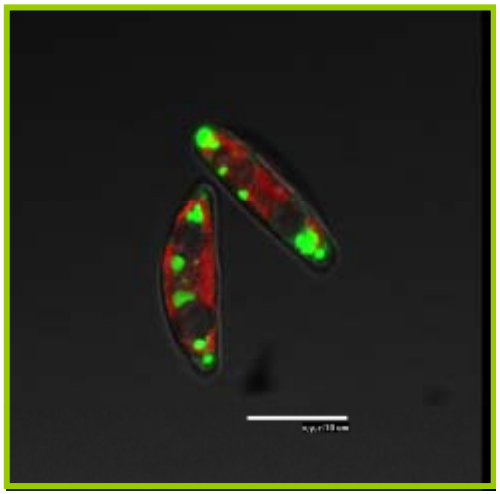




Why Fuels from Algal Oil?

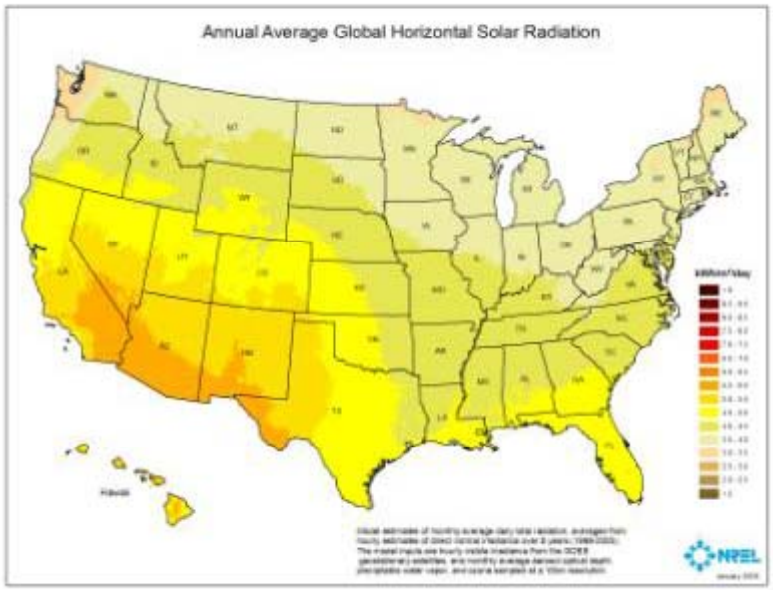


Images courtesy:
Lee Elliott, CSM



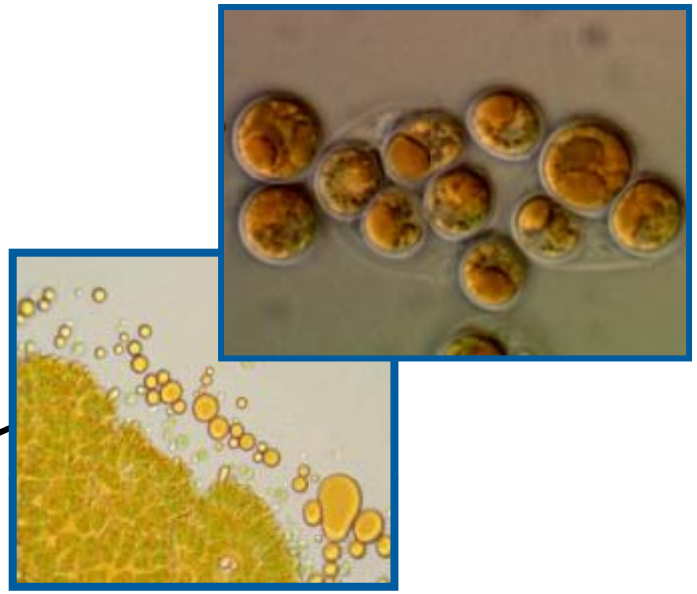
Fluorescence micrograph showing stained algal oil droplets (green)

- Microalgae have high-lipid content (60%); rapid growth rates (one doubling/day); produce more lipids per acre than other 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 gases)
- Potential to displace significant % U.S. diesel/jet fuel usage



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*



Images courtesy: Q. Hu, ASU

DOE's Aquatic Species Program (ASP)

- **DOE sponsored research project (1978-1996)**
- **Goal:** Develop renewable transportation fuels from algae
- **Focus:** Production of biodiesel from high lipid-content algae grown in ponds
- **Accomplishments:**
  - Advances in applied biology and design of algae production systems
  - 3,000 strains of algae collected and screened
  - 1,000 m^2 outdoor test facility operated for 12 continuous months in Roswell, New Mexico
  - Cost estimates for algal lipids $40 - $70 per bbl oil (Benemann and Oswald, 1996)
  - NREL's final report is still referenced and used as information/data source for algae researchers and implementers worldwide

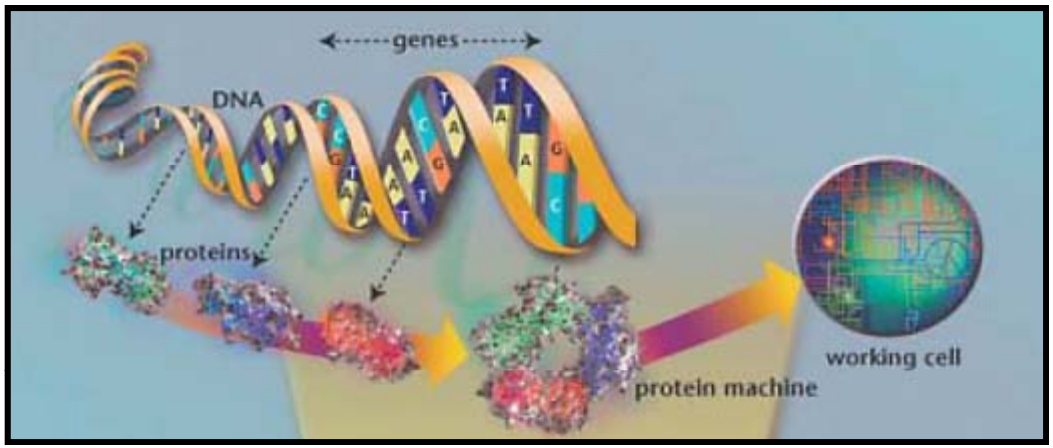
See the close-out report at:

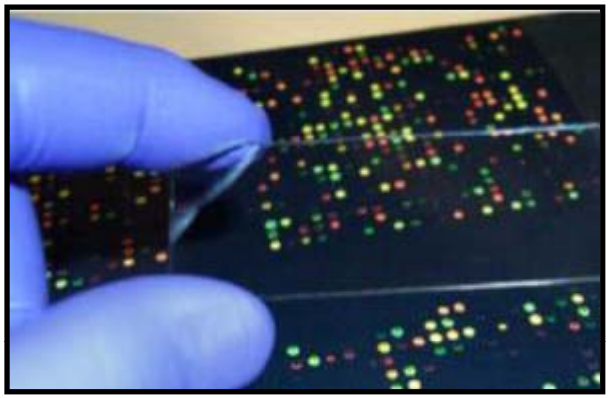
http://govdocs.aquake.org/cgi/reprint/2004/915/9150010.pdf

Termination reasons:
- **Decreasing federal budgets**
- **Focus on cellulosic ethanol**
- **Algal diesel not competitive with petro diesel at $20/barrel**

What's Changed Since 1996?

- **Record high crude oil prices (>$148/barrel)**
- **Emphasis on energy security/alternative biofuels**
- **CO_2 capture, carbon trading, GHG reduction**
- **Advances in photobioreactor designs/materials**
- **Explosion in biotechnology:** Advances in metabolic engineering and systems biology ("-omics")





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-Colorado Center for Biorefining and Biofuels (C2B2) sponsored research: Biofuels from algae (7/08)

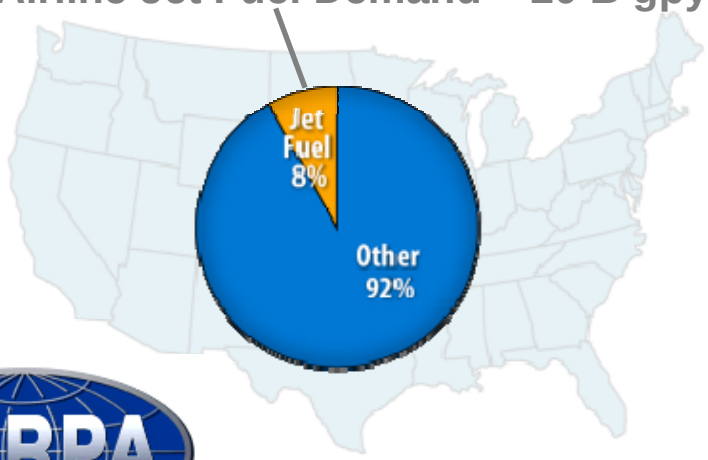
Growing Interest By End Users

- **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 with Algae-Link to procure algae oil to be blended with conventional jet fuel.
- **JetBlue, Airbus, Honeywell and the International Aero Engines partnership:** replace up to 30 percent of jet fuel with biofuels produced from algae and other non-food vegetable oils.
- **Air New Zealand:** test jatropha as a fuel

Growing Federal Interest

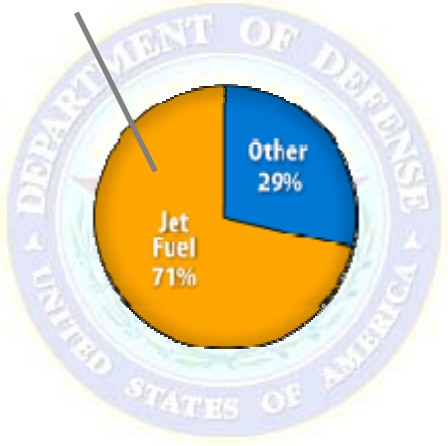
Commercial US Fuel Consumption

(US Airline Jet Fuel Demand ~ 20 B gpy)



DOD Fuel Consumption

DOD's Total Jet Fuel Demand ~ 5 B gpy



DARPA: Awarded $14.7M for 3 projects in 2007 (seed oil crops to JP8 jet fuel); 2 large algae teams in 2008 (algal oil-to-JP8 jet fuel)

DOE: $4.4M for six projects – two algae projects; Phase SBIR/STTRs

AFOSR: Four academic algal oil-to-jet fuel projects

Sandia National Laboratories

Pacific Northwest National Laboratory

Congressional Algae Report

2007 Energy Independence and Security Act (EISA)

- Increase availability of renewable energy that decreases GHG emissions and increases the Renewable Fuel Standard to 36 billion gallons by 2022.
- EISA required the Secretary of Energy to present a report to Congress within 90 days on the feasibility of microalgae as a feedstock for biofuels production (Section 228)

DOE Algal Biofuels Fact Sheet

- Prepared by DOE EERE Office of Biomass Programs (OBP) with NREL's assistance
- Provides a brief summary of the promise of algal biofuels and DOE efforts to make this promise a reality

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

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

National Algal Biofuels Technology Workshop

- Draw upon the expertise of a balanced group of scientists and other experts in the various required disciplines
- Input will help define activities needed to resolve uncertainties

- Planned and executed by DOE EERE OBP, NREL, SNL, and ORISE
- University of Maryland Inn and Conference Center, Dec. 9-10; initial roadmap writing session Dec. 11
- Plenary presentations and breakout sessions covering technical, industrial, resource, and regulatory aspects of algal biofuel production
- **Timetable**
  - December 9-11, 2008: Workshop
  - January 30, 2009: First draft of roadmap completed
    April 1, 2009: Final draft presented to DOE Office of Biomass Programs for distribution to scientific community

Venture Capital Investments Heating Up

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

LiveFuels: raised $10M Series A (2007)

Aurora BioFuels: raised $20M; open-pond

Sapphire Energy: raised $100M

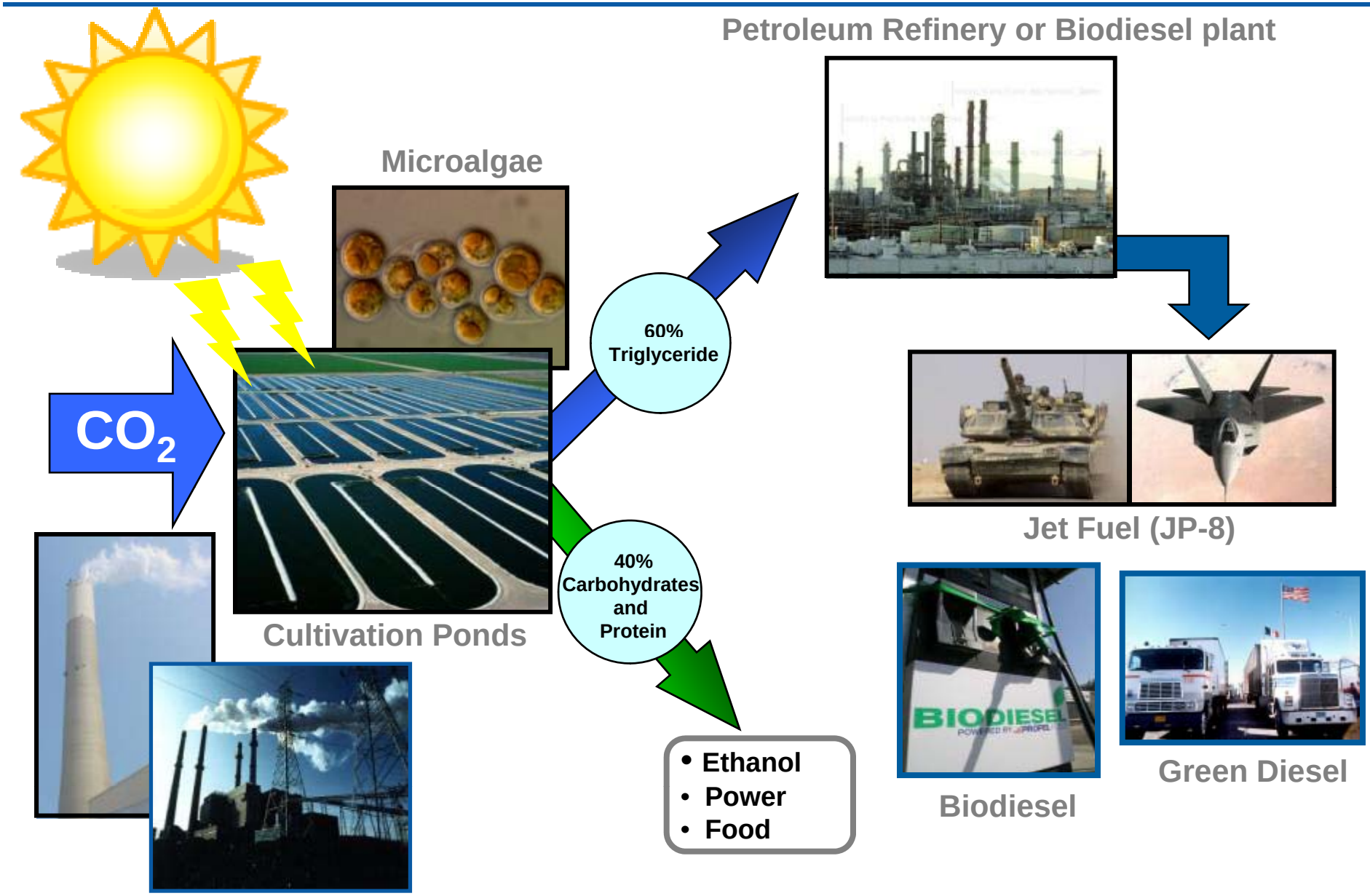
Solazyme: raised $45M; algae growing in the fermentors (in the dark with sugars)

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

Growing Industrial Interest

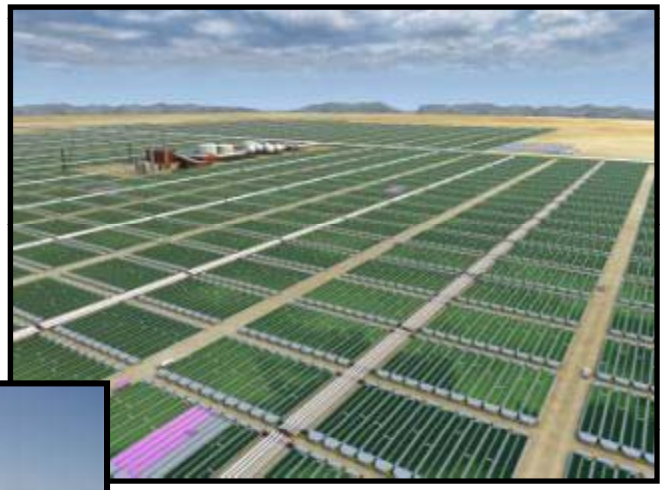
A2BE Carbon Capture, LLC
Algae Biofuels
Algae Link
AlgaeWheel
Algenol (ethanol)
Algodyne
Algoil
AlgroSolutions
Aquaflow Bionomic
Aquatic Energy
Aurora BioFuels Inc.
Bionavitas
Blue Biofuels
Blue Marble Energy
Bodega Algae
Cequesta
Circle Biodiesel & Ethanol
Community Fuels
Diversified Energy
Energy Farms
Enhanced Biofuels & Technologies
General Atomics
Global Green Solutions
Green Star
Greenfuel Technologies Corp
GreenShift (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

Production of Fuels from Algae



No shortage of cultivation ideas…





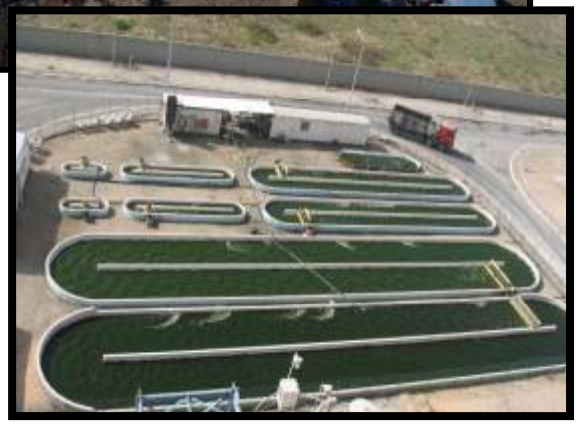
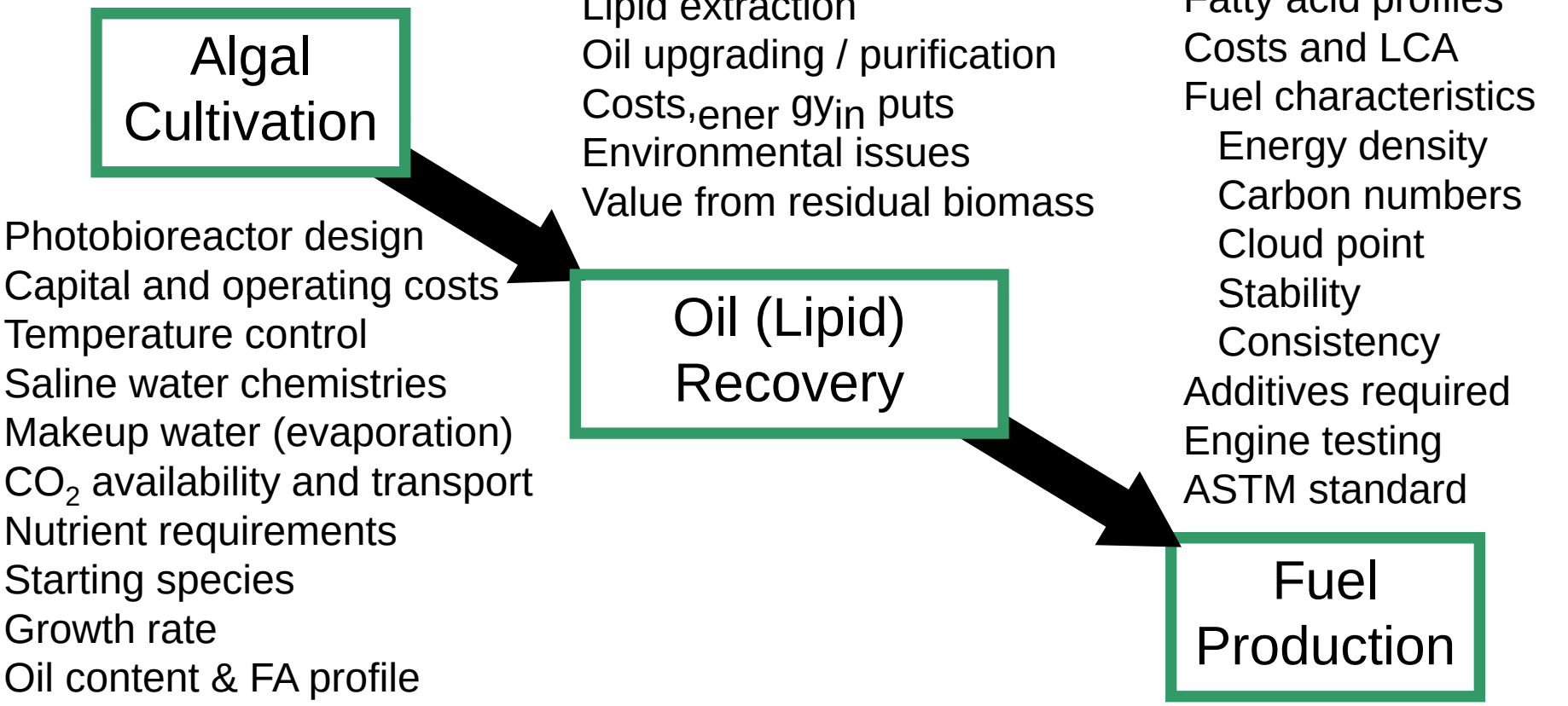



Image courtesy: A. Ben-Amotz, Seambiotic

Technical challenges



Summary

Promises

- **Technical feasibility has been demonstrated**
  - Microalgae can make oil (TAGs) from sunlight/CO_2
  - TAGs can be used to make a variety of fuels
  - Algae represent new feedstock for biofuels – doesn't compete with food production or water/land resources
  - Potential to supply significant percentage of U.S. fuel demand

Challenges

- **Economic feasibility has yet to be demonstrated**
  - Basic and applied algal biology
  - Process engineering research
  - Production and integrated process scale-up
  - Technoeconomic (TE) and Life Cycle Analysis (LCA)
  - Environmental and social issues

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