The Promise & Challenges for Algae Biofuels

SAND2010-0993C

Overview of Approaches and Issues for Sustainable Production Scale-up

Exceptional Service In the National Interest

ADVANCING SCIENCE, SERVING SOCIETY

Symposium:

Algae for Food, Feed, Fiber, Freshwater, & Fuel

February 19, 2010
1:30 PM – 4:30 PM

San Diego Convention Center
San Diego, CA

Ron Pate
Sandia National Laboratories
Albuquerque, NM
and
DOE/EERE Office of Biomass Program
Washington, DC

rcpate@sandia.gov, (505) 331-0608
ronald.pate@ee.doe.gov, (202) 287-5207

National Nuclear Security Administration

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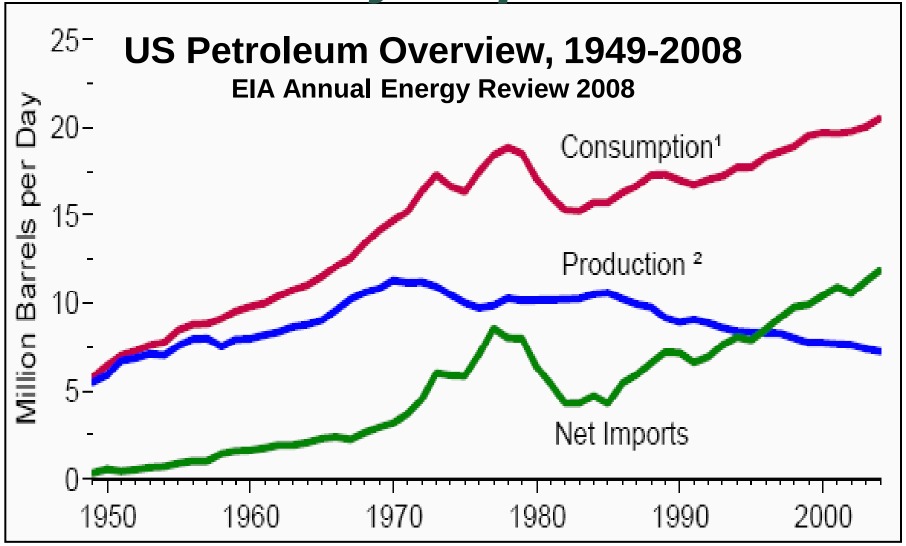
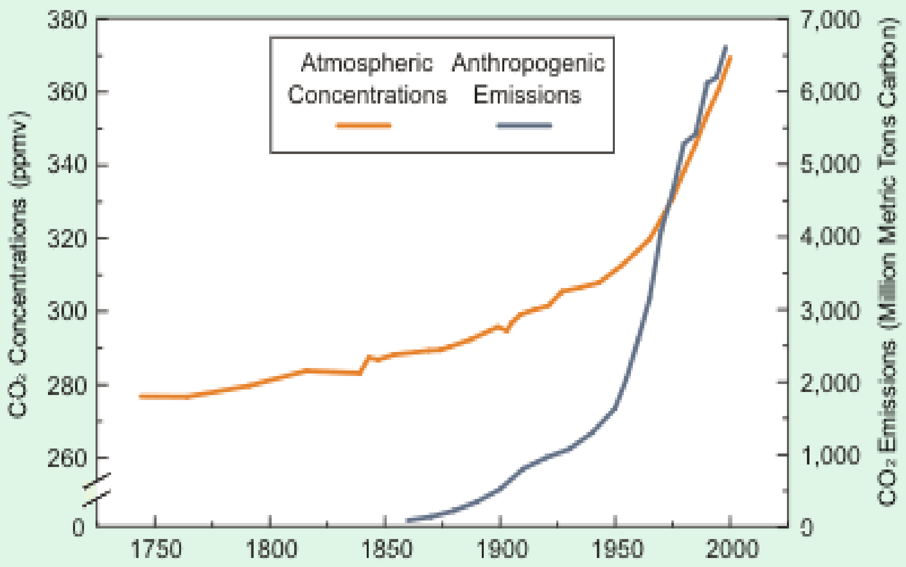
Context & Motivation: *Confluence of Trends with Serious Economic and National Security Implications*

"The peaking of world oil production presents the U.S. and the world with an unprecedented risk management problem. As peaking is approached, liquid fuel prices and price volatility will increase dramatically, and, without timely mitigation, the economic, social, and political costs will be unprecedented. Viable mitigation options exist on both the supply and demand sides, but to have substantial impact, they must be initiated more than a decade in advance of peaking."

- *Bob Hirsch, et.al. (2005).* Peaking Of World Oil Production: Impacts, Mitigation, & Risk Management



1 Petroleum products supplied used as approximation for consumption.
2 Crude oil and natural gas plant liquids production.



Source: Oak Ridge National Laboratory, Carbon Dioxide Information Analysis Center, http://cdiac.esd.ornl.gov/.

"Climate change can act as a threat multiplier for instability in some of the most volatile regions of the world, and it presents significant national security challenges for the United States."

- Joshua Busby, *Climate Change and National Security: An Agenda for Action*, COUNCIL ON FOREIGN RELATIONS, CSR NO. 32, NOVEMBER 2007

"We already know enough to appreciate that the cascading consequences of unchecked climate change are to include a range of security problems that will have dire global consequences."

- CSIS/CNAS, *The Age of Consequences: The Foreign Policy and National Security Implications of Global Climate Change, November 2007; available at http://www.cnas.org/climatechange*

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Snap-Shot of U.S. Transportation
Fuel Use and CO_2 Emissions

- Breakdown of Annual U.S. Fuel Use for Transportation:
  - Gasoline blends: ~140-B gal/yr
  - Diesel: ~ 45-B gal/yr
  - Aviation: ~ 25-B gal/yr
  - Total: ~ 210-B gal/yr
- Burning each of these fuels produces ~ 20 pounds of CO_2 per gallon
- 210-B gal/yr x 20-lbs CO_2/gal ~ 2.1 Billion tons of CO_2 emitted per year
- Compared with ~ 4-Billion tons CO_2 from stationary sources (power plants, cements plants, ethanol plants, etc.)
- Capture and sequestration of CO_2 and/or re-use of emitted carbon from transportation vehicles is impractical

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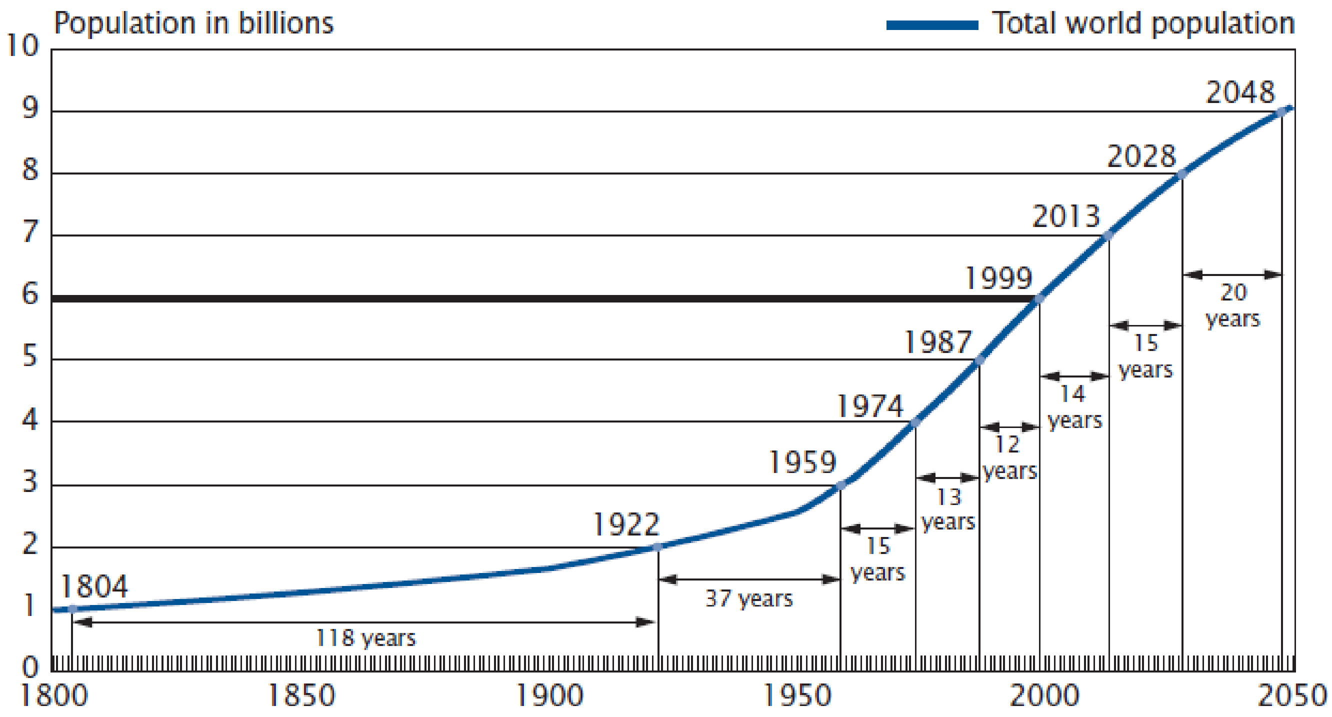
Context & Motivation: *Confluence of Trends with Serious Geo-Political and Global Stability Implications*

Annual Additions and the Annual Growth Rate of Global Population

The growth of global population has peaked.



Source: United Nations, *World Population Prospects: The 1994 Revision*; U.S. Census Bureau, International Programs Center, International Data Base and unpublished tables.

"The World Bank estimates that demand for food will rise by 50 percent by 2030, as a result of growing world population, rising affluence, and shifts to Western dietary preferences by a larger middle class."

Consequence for biofuels : ***Must avoid long-term conflict with agriculture for land, water, & fertilizer required for food & feed production***

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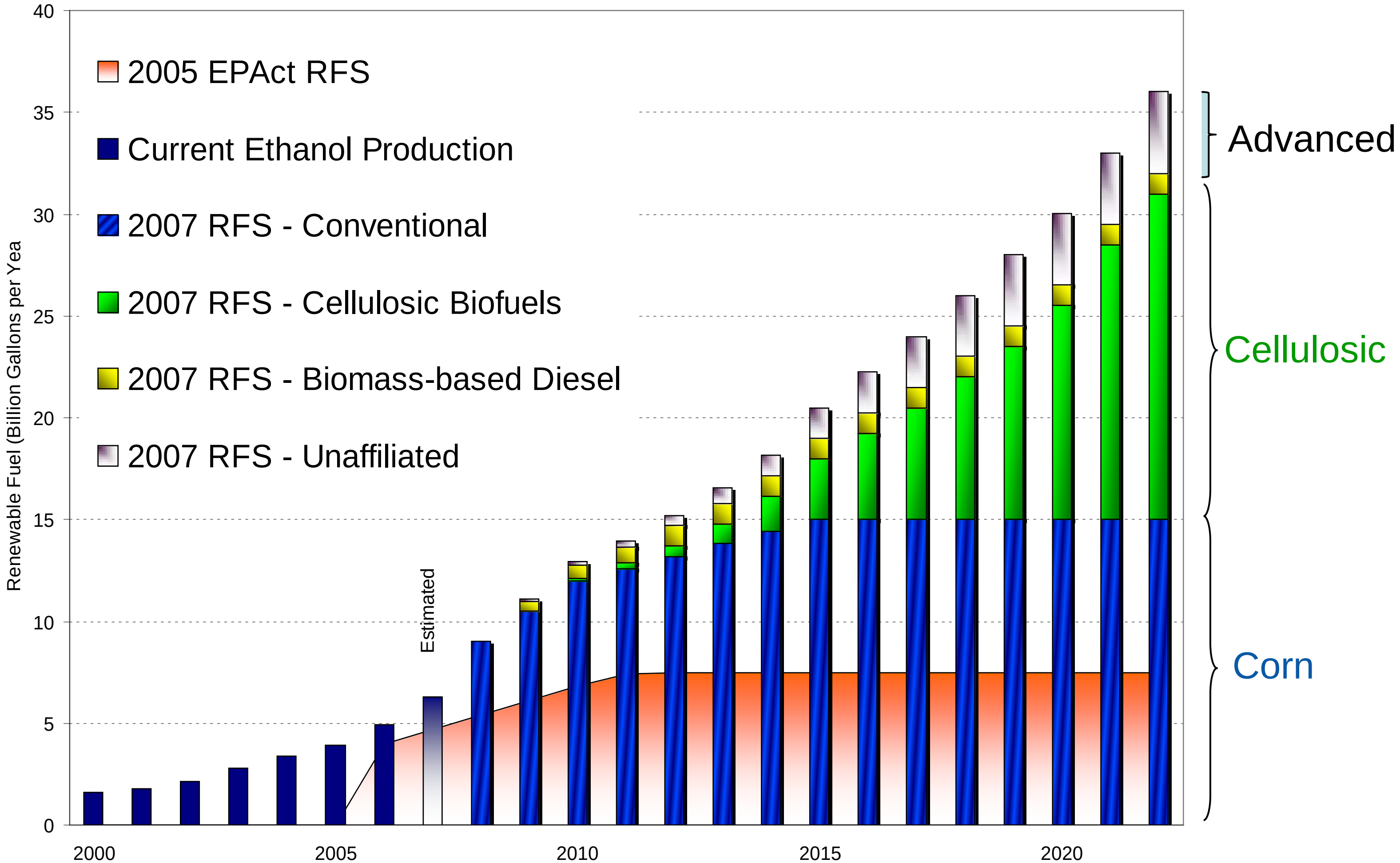
Policy Driver: *Advanced Biofuels in 2007 EISA Renewable Fuel Standard*

36 billion gallons of renewable fuels by 2022



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

Biofuels Challenge: Sustainable Scale-Up

Water: Key Factor for Sustainable Biofuels

A Growing Awareness of Energy-Water Interdependencies

Water Use
by Ethanol Plants

Potential Challenges

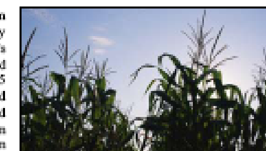
Institute for Agriculture and Trade Policy

THE NATIONAL ACADEMIES

REPORT IN BRIEF

October 2007

Water Implications of Biofuels Production in the United States



production based on discussions at the colloquium, written submissions of participants, the peer-reviewed literature, and the best professional judgments of the committee.

Types of Biofuels

Currently, the main biofuel in the United States is ethanol derived from corn kernels. Corn-based ethanol is made by converting the starch in corn kernels to sugars and then converting those sugars into ethanol. Ethanol derived from sorghum and biodiesel derived from soybeans comprise a very small fraction of U.S. biofuels. Other potential sources of materials for use in biofuels include field crops such as soy; short-rotation woody crops such as poplar and willow; animal fats, vegetable oils, and recycled greases; perennial grasses, such as switchgrass; agricultural ...

... National Research Council

The New York Times
nytimes.com

October 11, 2007

Panel Sees Problems in Ethanol Production

By CORNELIA DEAN

Greater cultivation of crops to produce ethanol could harm water quality and leave some regions of the country with water shortages, a panel of experts is reporting. And corn, the most widely grown fuel crop in the United States, might cause more damage per unit of energy than other plants, especially switchgrass and native grasses, the panel said.

BusinessWeek

About Our New Look

THE ASSOCIATED PRESS October 11, 2007, 11:58AM ET

India, China biofuels may sap water

By MICHAEL CASEY

BANGKOK, THAILAND

China's and India's plans to produce more biofuels could cause shortages of water, which is needed for crops to feed their growing populations, according to a water study released Thursday.

The International Water Management Institute or IWMI study said both countries are counting on maize and sugarcane, which need large amounts of water, for much of their biofuels.

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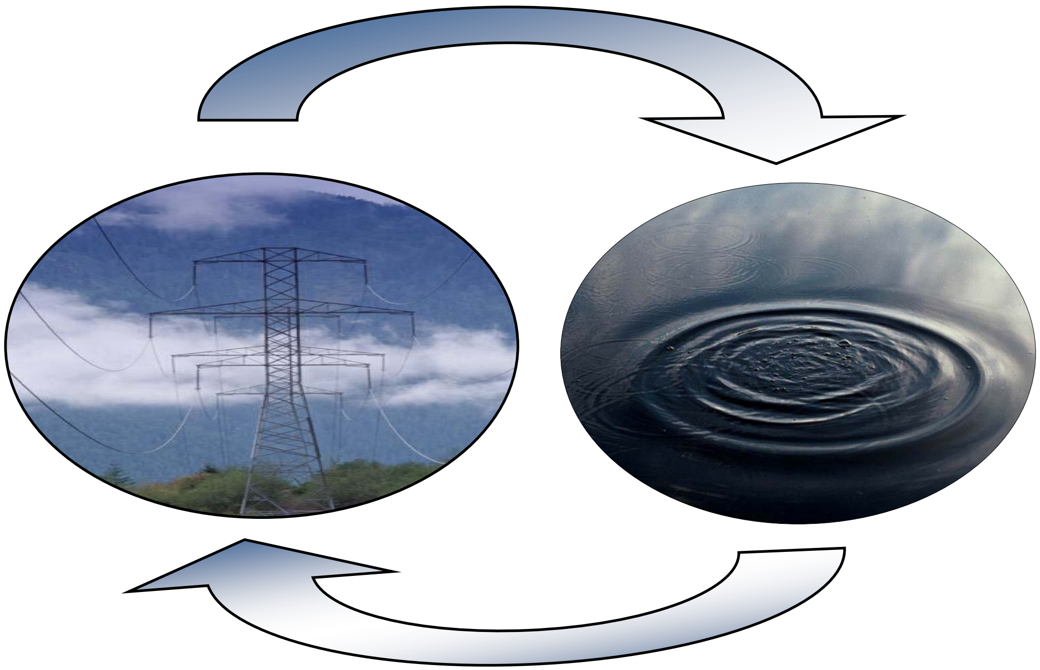
The *Energy-Water Nexus*
Energy and Water are Inextricably linked

<u>Water for Energy</u> and ***<u>Energy for Water</u>***

Energy and power production requires water:

- Thermoelectric cooling
- Hydropower
- Energy minerals extraction / mining
- Fuel Production (fossil fuels, H_2, **biofuels**, other non-conventional fuels)
- Emission controls



Water production, processing, distribution, and end-use requires energy:

- Pumping
- Conveyance and Transport
- Treatment
- Use conditioning
- Surface and Ground water

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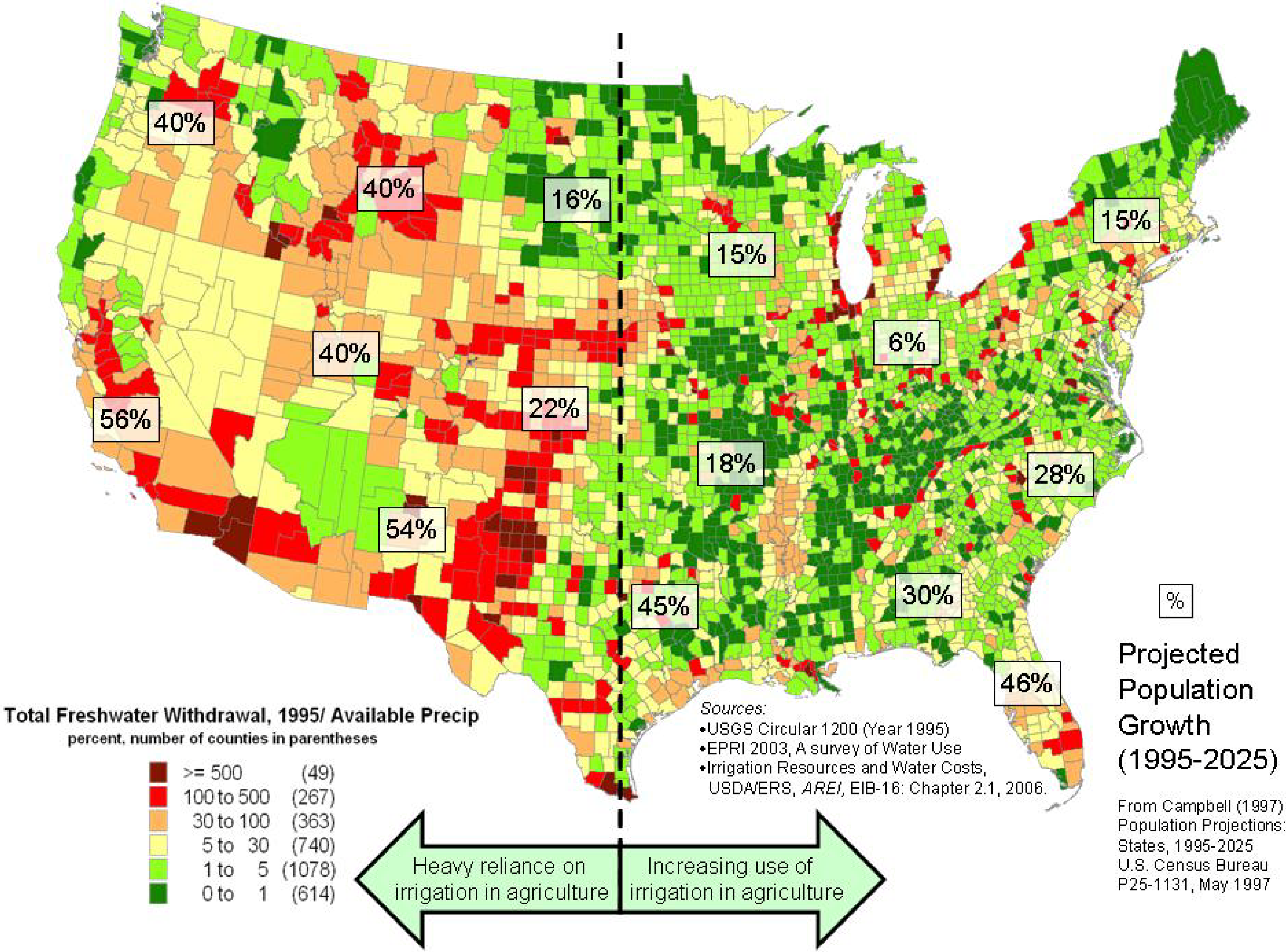
Water Challenges are Nationwide



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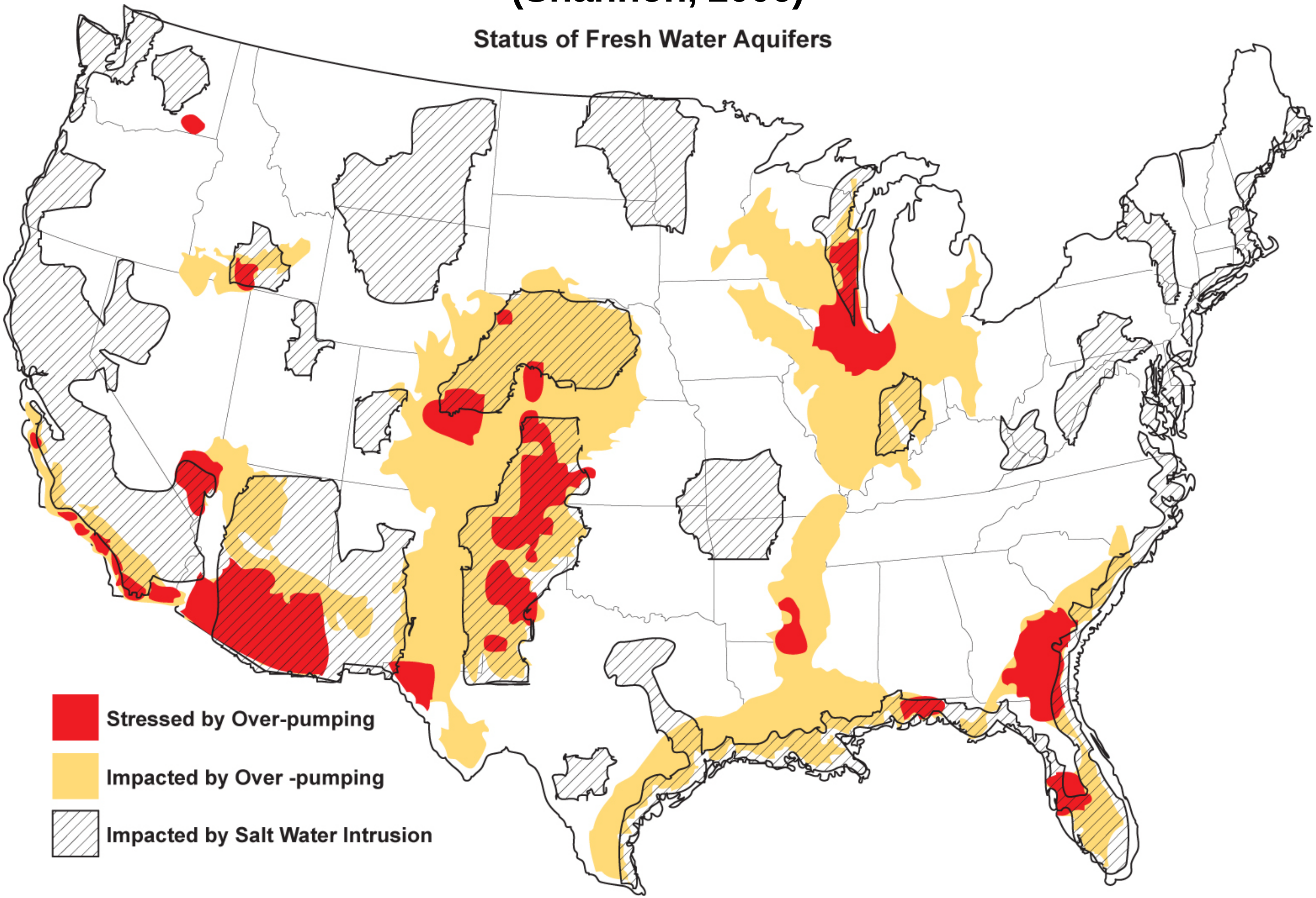
Aquifers Impacted by Over-Pumping

(Shannon, 2006)



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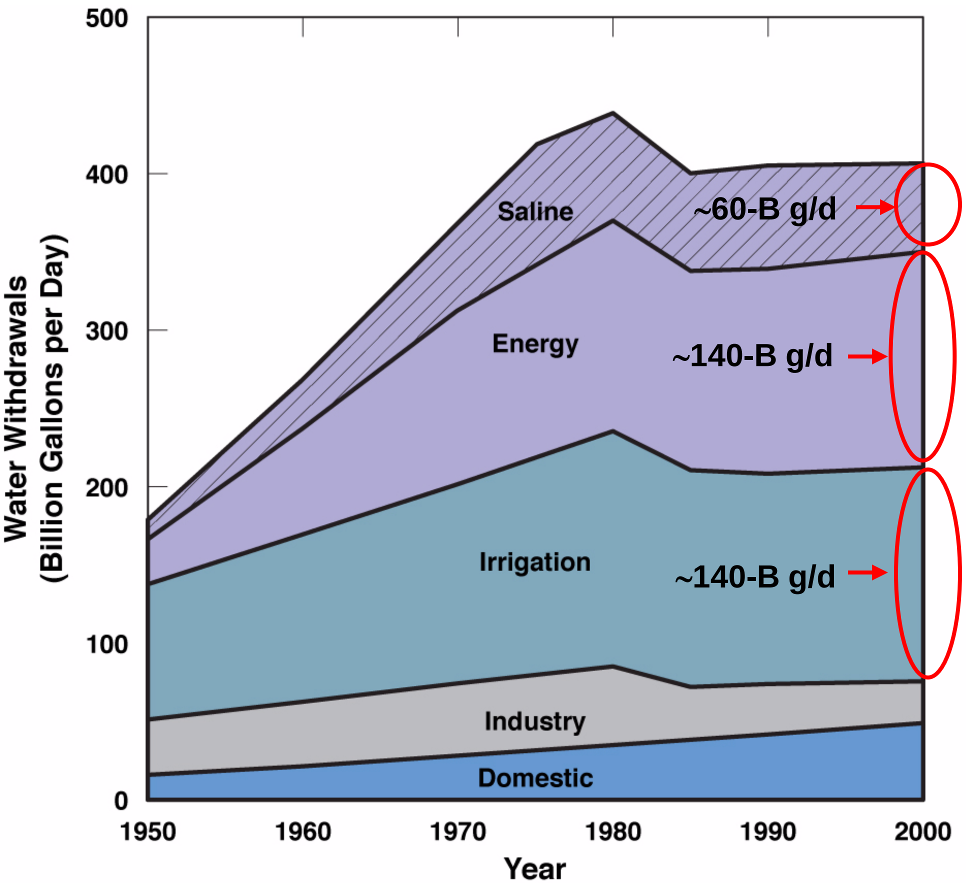
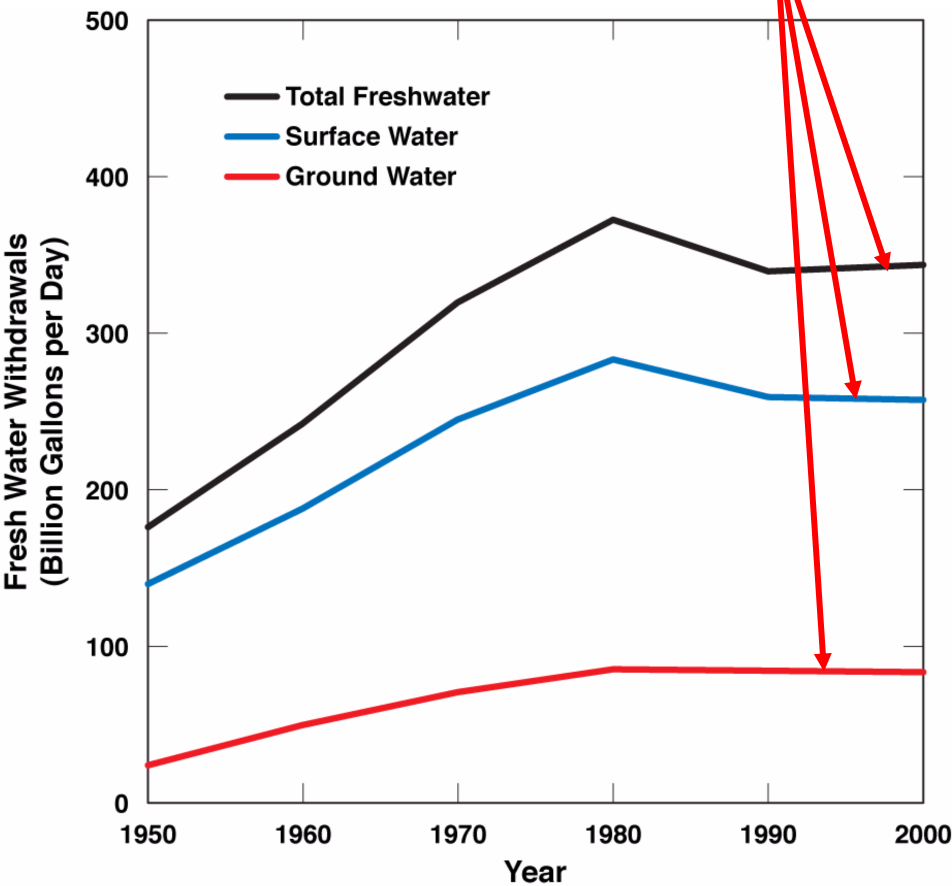
Trends in U.S. Water Withdrawals
1950-2000 (Hutson, et.al., 2004)

Recent Trends Flat … Approaching Full Supply Allocation





Major Biofuel Production Scale-Up Will Need to Include Exploitation of Non-Fresh Water Sources

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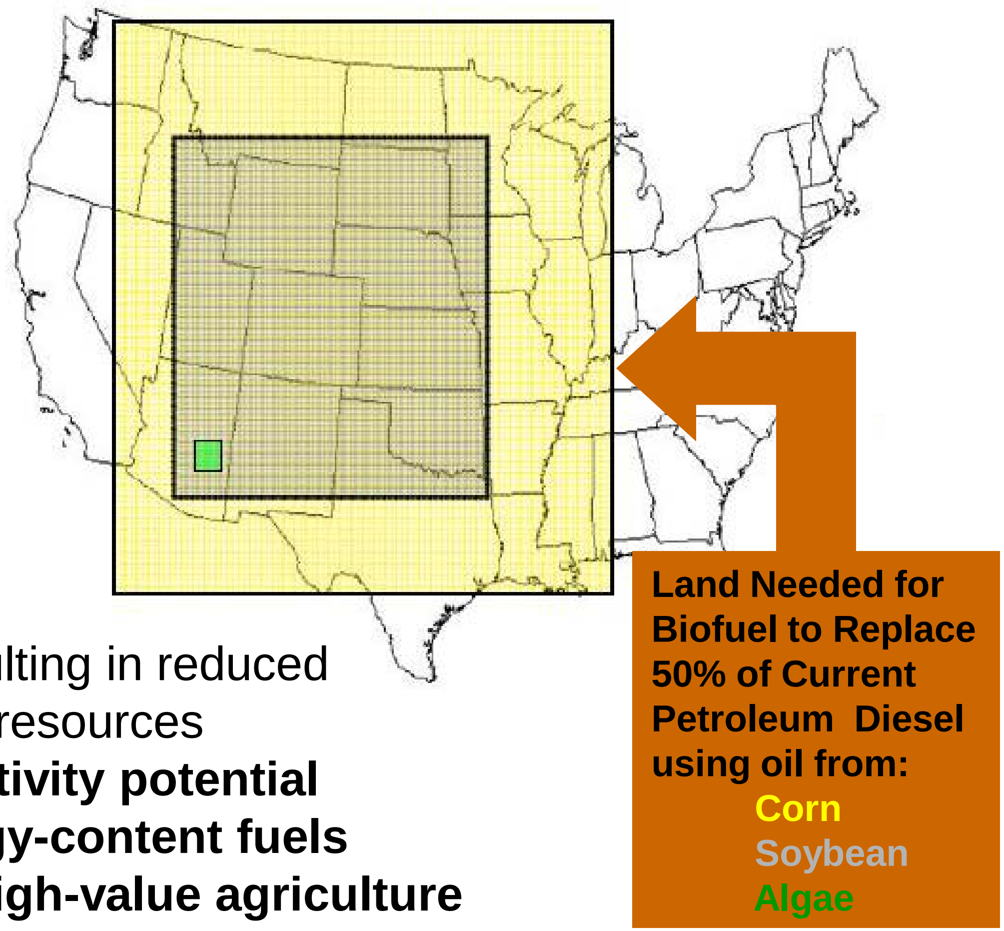
The Promise of Algae-Based Biofuels

Algae has potential advantages over corn, cellulosic materials, and other crops as an alternative to petroleum-based fuels

Gallons of Oil per Acre per Year	
Corn	18
Soybeans	48
Rapeseed	127
Oil Palm	635
Micro Algae	1000 - 7000



- **Can use non-fresh water**, resulting in reduced pressure on limited fresh water resources
- **High biomass &/or oil productivity potential**
- **Oil feedstock for higher energy-content fuels**
- **Can avoid competition with high-value agriculture**
  e.g., land, water, and markets for food & feed production
- **Captures CO_2 and recycles carbon** for fuels and co-products

Algae Biofuels:
Numerous Approaches and Paths

Algae

Unicellular MicroAlgae | Cyanobacteria | Multi-cellular MiacroAlgae

Species Selection & Biology

Open Terrestrial Systems | Hybrid Systems | Closed Terrestrial Systems | Off-Shore Systems

Mixotrophic | Phototrophic | Phototrophic | Heterotrophic | Phototrophic

Cultivation Systems
+
- Harvesting
- Dewatering
- Fractionation
- Separation

Hydrocarbons & Alcohols* | Lipids | Carbohydrates | Proteins | Consolidated Biomass

Intermediate Constituents

* Biologically produced in-situ by the organism

Biochemical Conversion | Thermochemical Conversion | Anaerobic Digestion | Direct Synthesis

Conversion Processes

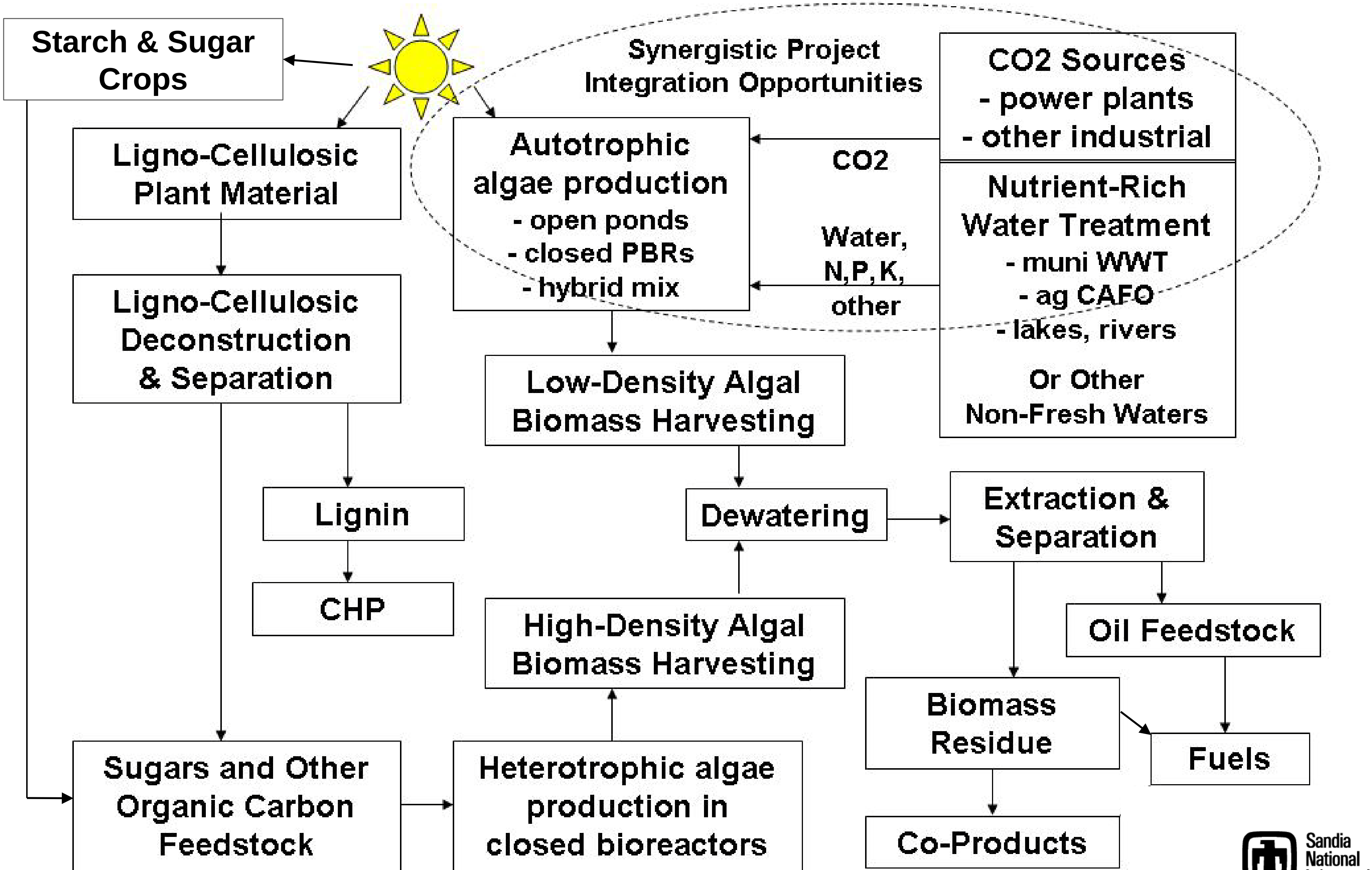
Renewable Hydrocarbons | Biodiesel | Alcohols | Biogas | Co-Products

End Use Fuels & Products

Adapted from DOE/EERE OBP Algae Roadmap Report

Phototrophic & Heterotrophic Paths

... Linked Back To Photosynthesis



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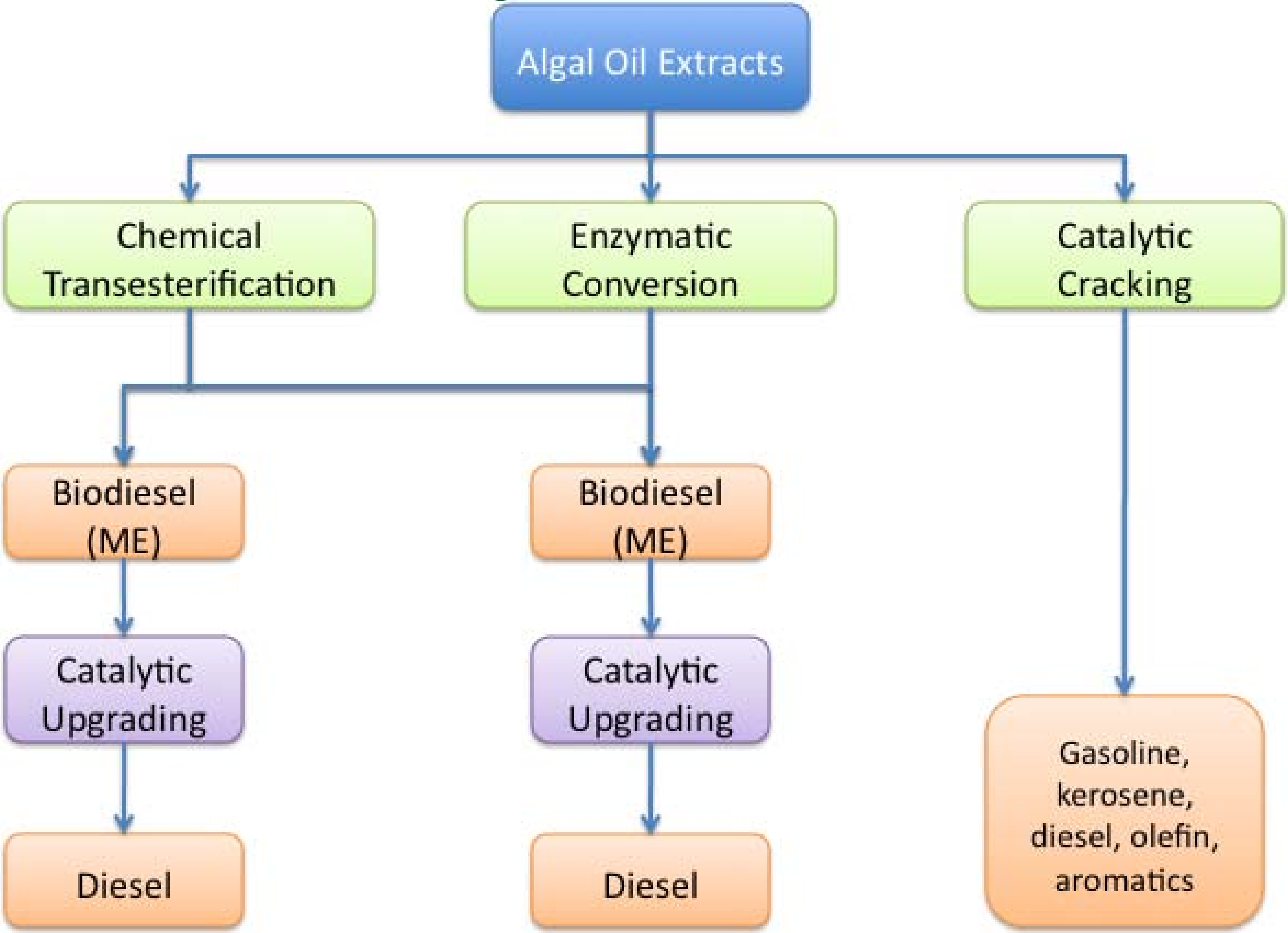
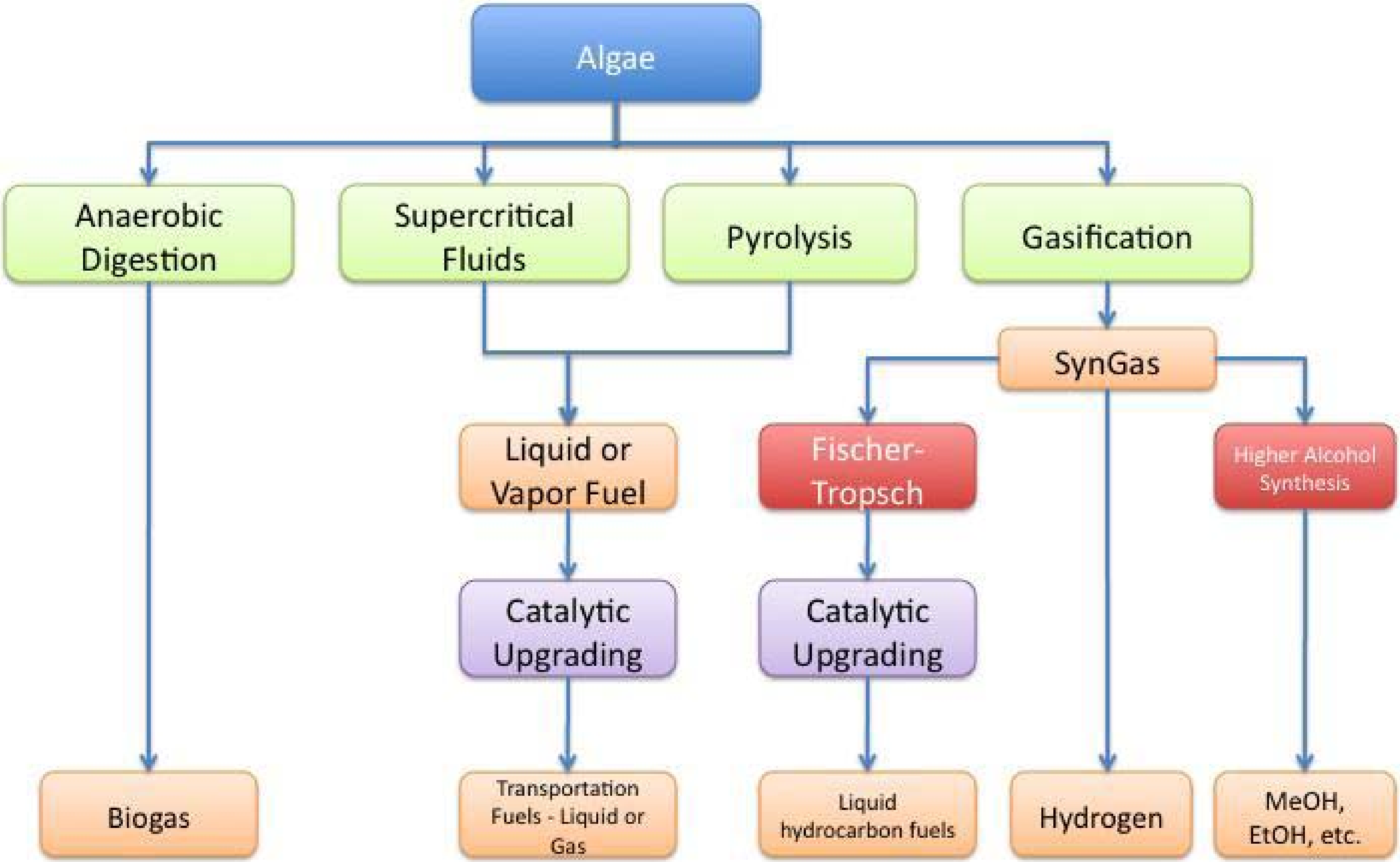
Example Conversion Paths for Algal Oil to Biofuels



Adapted from Draft DOE/EERE OBP Algae Roadmap Report

Example Conversion Paths for Algal Biomass to Biofuels

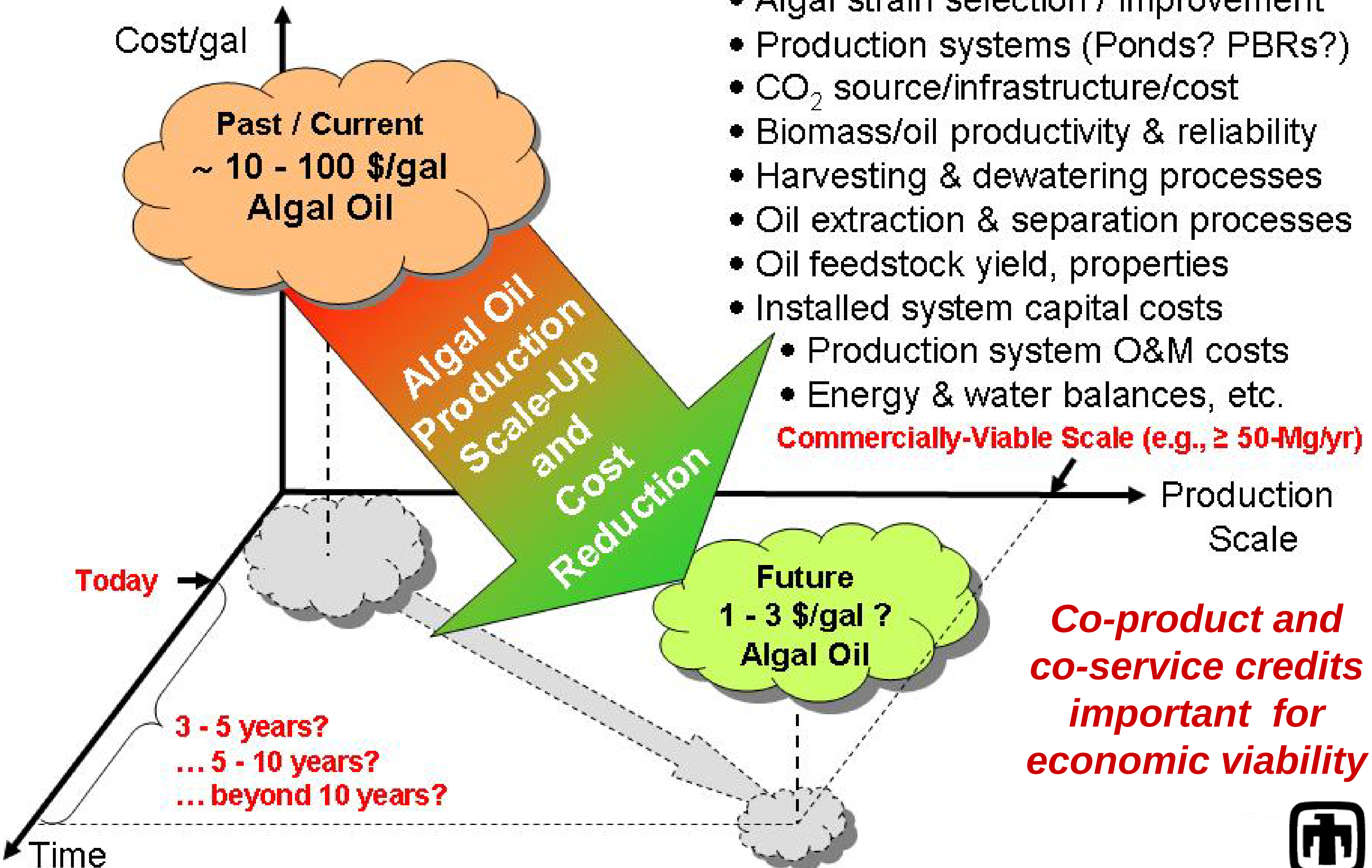


Adapted from Draft DOE/EERE OBP Algae Roadmap Report

Cost & Scale-up Challenges for Algal Biofuels

Examples of Systems and Processes Issues

- Algal strain selection / improvement
- Production systems (Ponds? PBRs?)
- CO_2 source/infrastructure/cost
- Biomass/oil productivity & reliability
- Harvesting & dewatering processes
- Oil extraction & separation processes
- Oil feedstock yield, properties
- Installed system capital costs
  - Production system O&M costs
  - Energy & water balances, etc.



Co-product and co-service credits important for economic viability

Preliminary
Resource Consequence
Analysis

Based on

Three Hypothetical
Regional Scale-up Scenarios
for
Algal Oil Production

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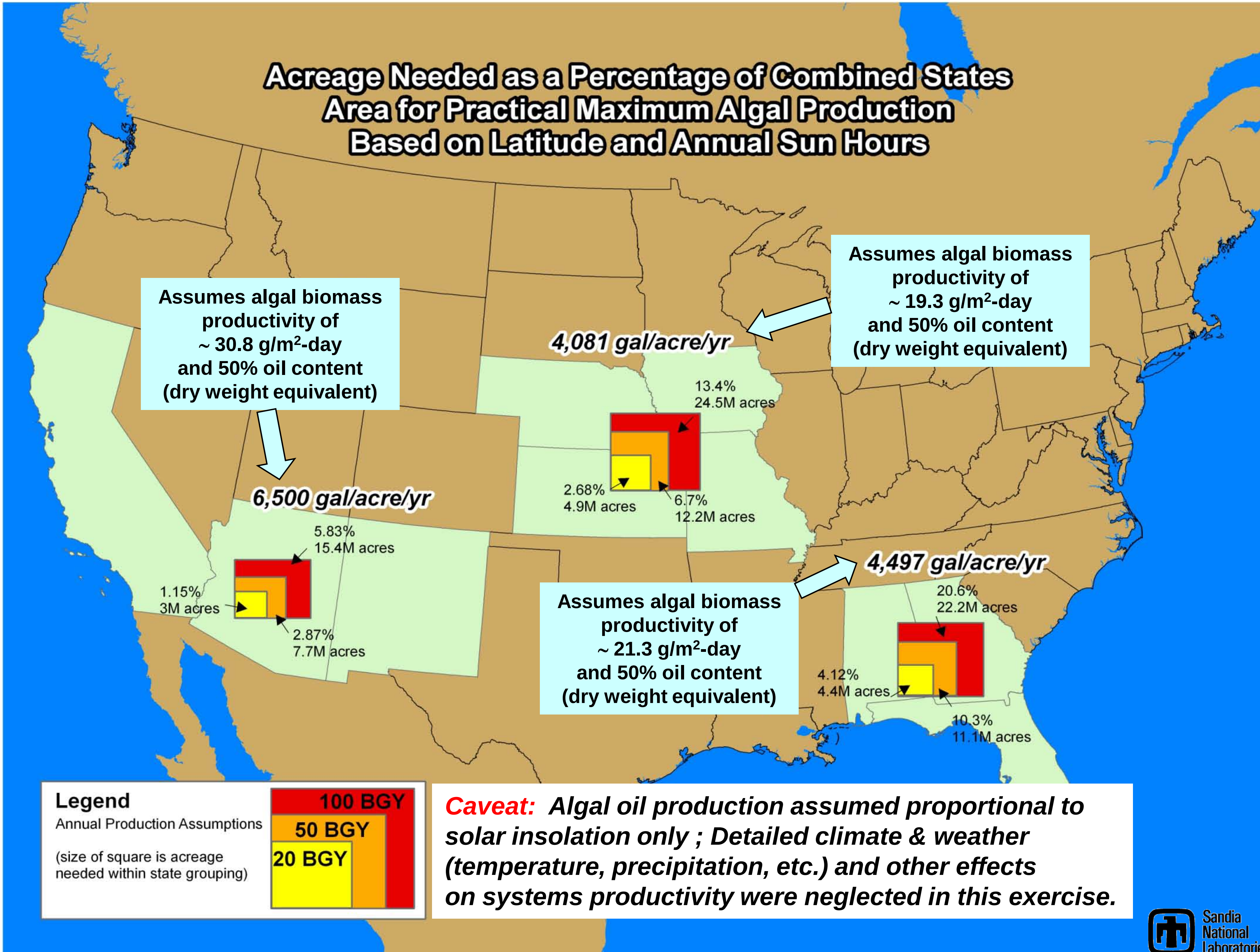
Acreage Needed as a Percentage of Combined States
Area for Practical Maximum Algal Production
Based on Latitude and Annual Sun Hours
Assumes algal biomass productivity of ~ 30.8 g/m2-day and 50% oil content (dry weight equivalent)
6,500 gal/acre/yr
5.83%
15.4M acres
1.15%
3M acres
2.87%
7.7M acres
4,081 gal/acre/yr
13.4%
24.5M acres
2.68%
4.9M acres
6.7%
12.2M acres
Assumes algal biomass productivity of ~ 19.3 g/m2-day and 50% oil content (dry weight equivalent)
Assumes algal biomass productivity of ~ 21.3 g/m2-day and 50% oil content (dry weight equivalent)
4,497 gal/acre/yr
20.6%
22.2M acres
4.12%
4.4M acres
10.3%
11.1M acres
Legend
Annual Production Assumptions
(size of square is acreage needed within state grouping)
100 BGY
50 BGY
20 BGY
Caveat: Algal oil production assumed proportional to solar insolation only ; Detailed climate & weather (temperature, precipitation, etc.) and other effects on systems productivity were neglected in this exercise.
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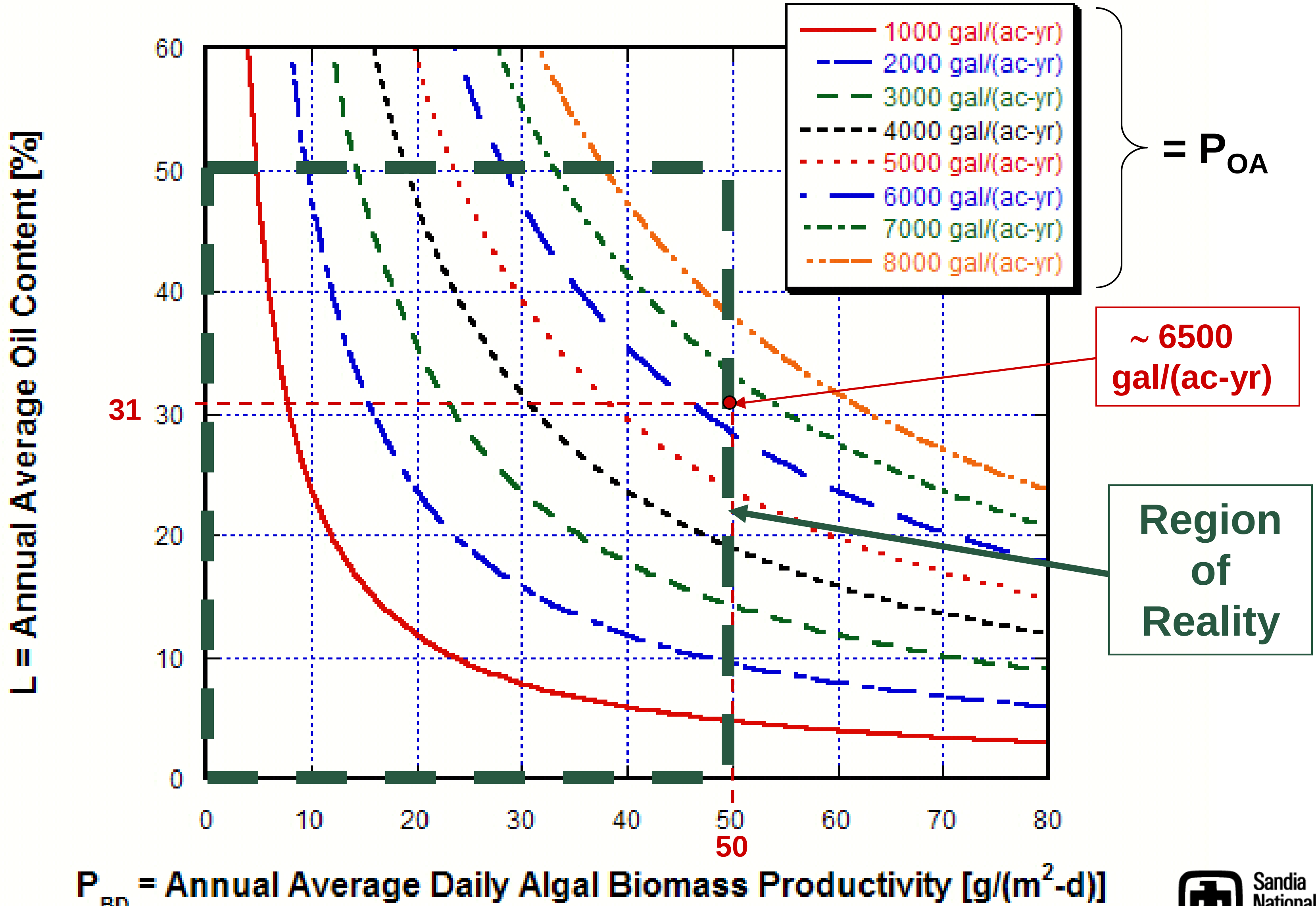
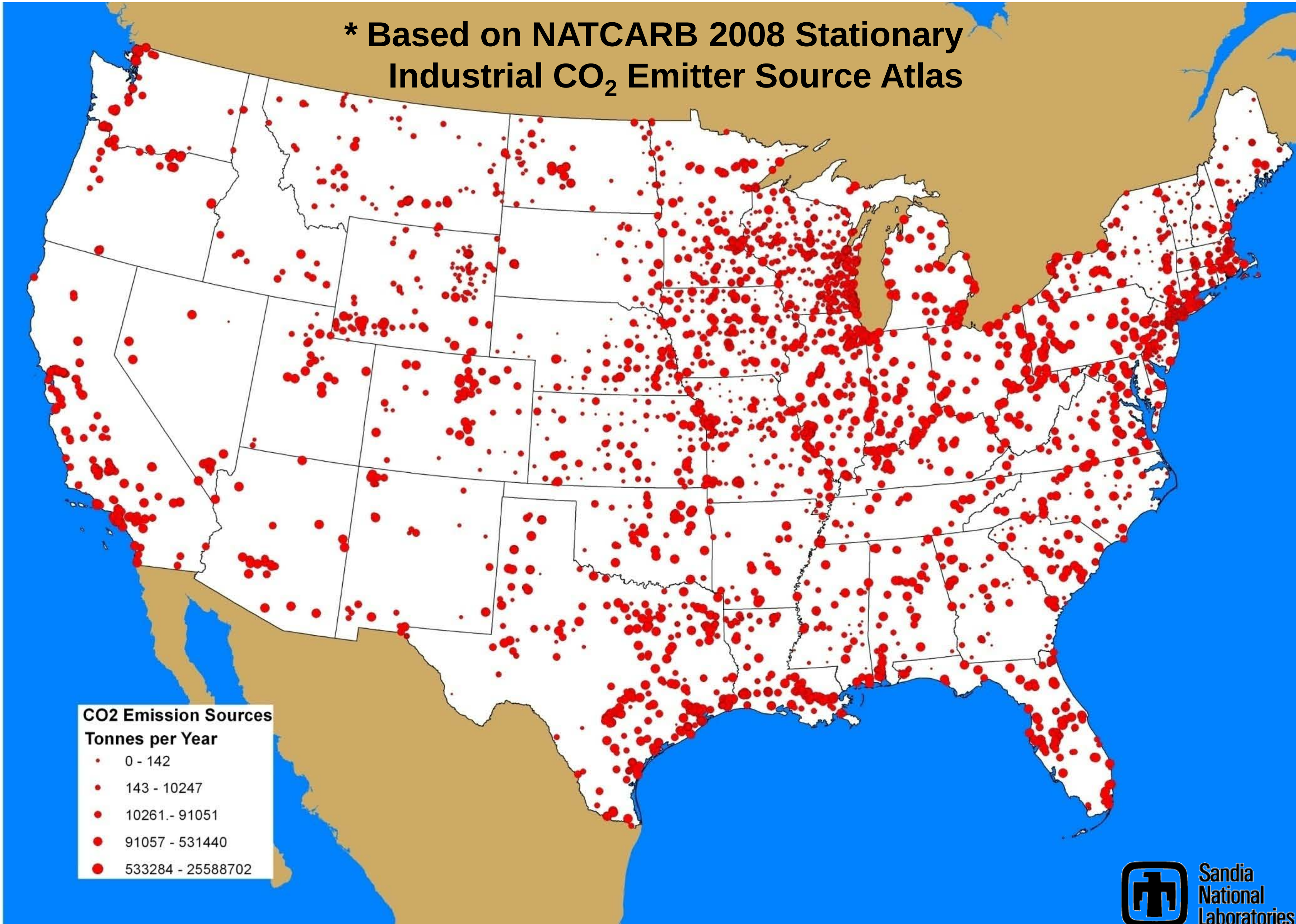
Algal Oil Productivity Parametric Curves

$$P_{OA}\ [\text{gal/(ac-yr)}] = 4.222 \times L\ [\%] \times P_{BD}\ [\text{g/(m}^2\text{-d)}]$$

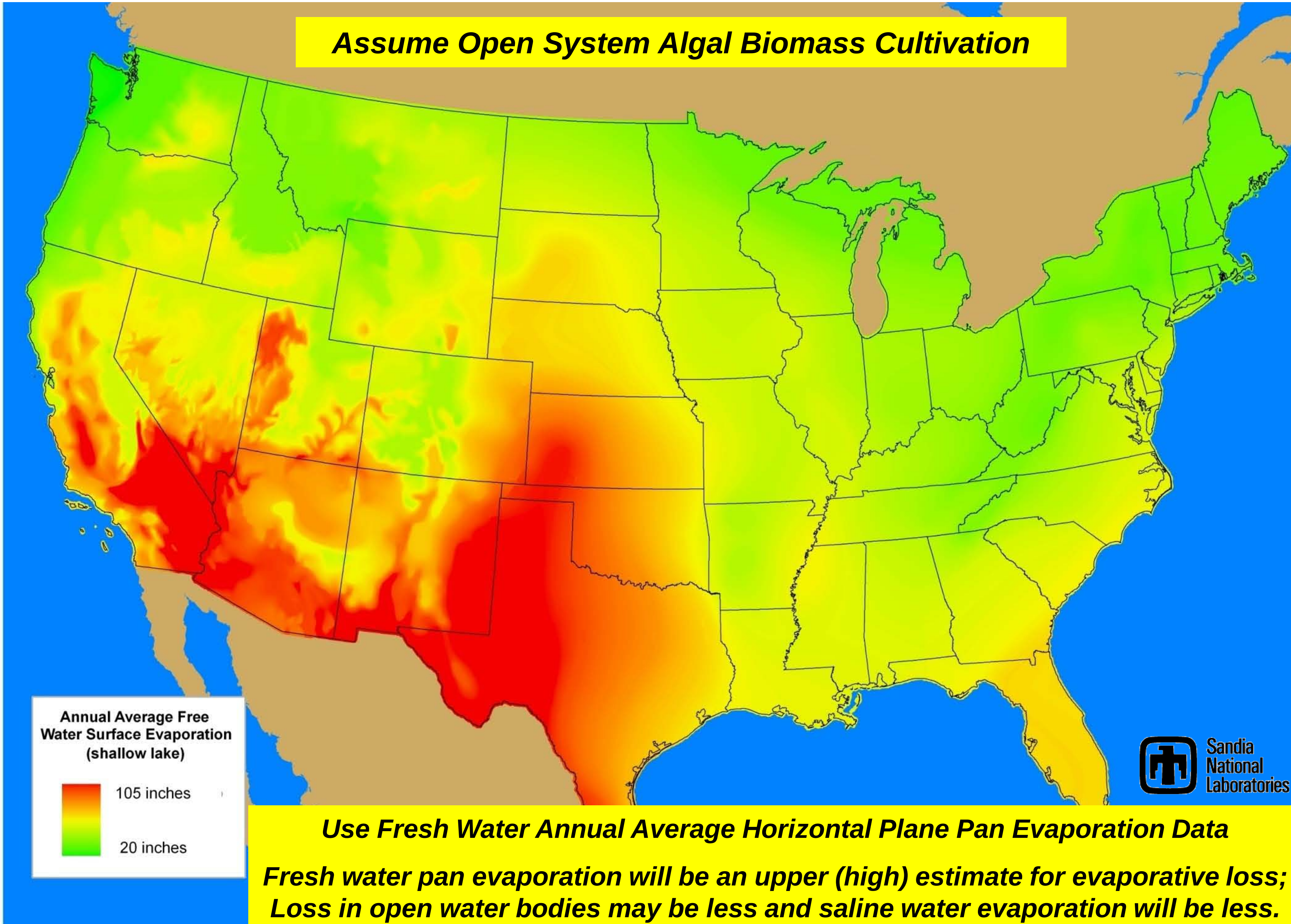


Factor in US* Distribution of CO_2 Sources



Factor in Evaporative Water Loss

Assume Open System Algal Biomass Cultivation



Use Fresh Water Annual Average Horizontal Plane Pan Evaporation Data

Fresh water pan evaporation will be an upper (high) estimate for evaporative loss; Loss in open water bodies may be less and saline water evaporation will be less.

LAND USAGE	20 BGY	50 BGY	100 BGY	20 BGY	50 BGY	100 BGY
	Land Required (1000s of acres)			% of Selected Land Classes*		
Southwest	3,077	7,692	16,385	2.5	6.2	13.3
Midwest	4,900	12,251	24,502	9.1	22.7	45.4
Southeast	4,447	11,119	22,237	30.3	75.8	152

* Combination of grassland pasture, range, and other**
**Misc. uses not inventoried, desert, bare rock areas, marshes, etc.

CO_2 USAGE	20 BGY	50 BGY	100 BGY	20 BGY	50 BGY	100 BGY
	Required CO_2 (millions of metric tonnes)			% of total CO_2 emissions from sources in scenario region*		
Southwest	279.8	699.5	1399	145	363	725
Midwest	279.8	699.5	1399	129	322	643
Southeast	279.8	699.5	1399	89.6	224	448

*As reported in NATCARB 2008 stationary source data base

EVAPORATIVE WATER LOSS	20 BGY	50 BGY	100 BGY	20 BGY	50 BGY	100 BGY
	Water loss* (trillions of gallons per year)			Evaporative loss as % of total water used for irrigation in region		
Southwest	5.47	12.1	22.3	26.4	58.4	108
Midwest	6.54	15.1	28.3	69.8	162	304
Southeast	5.03	12.6	25.2	47.6	119	239

*Based on annual average freshwater pan evaporation (worst-case)

SCENARIOS
Resource Usage

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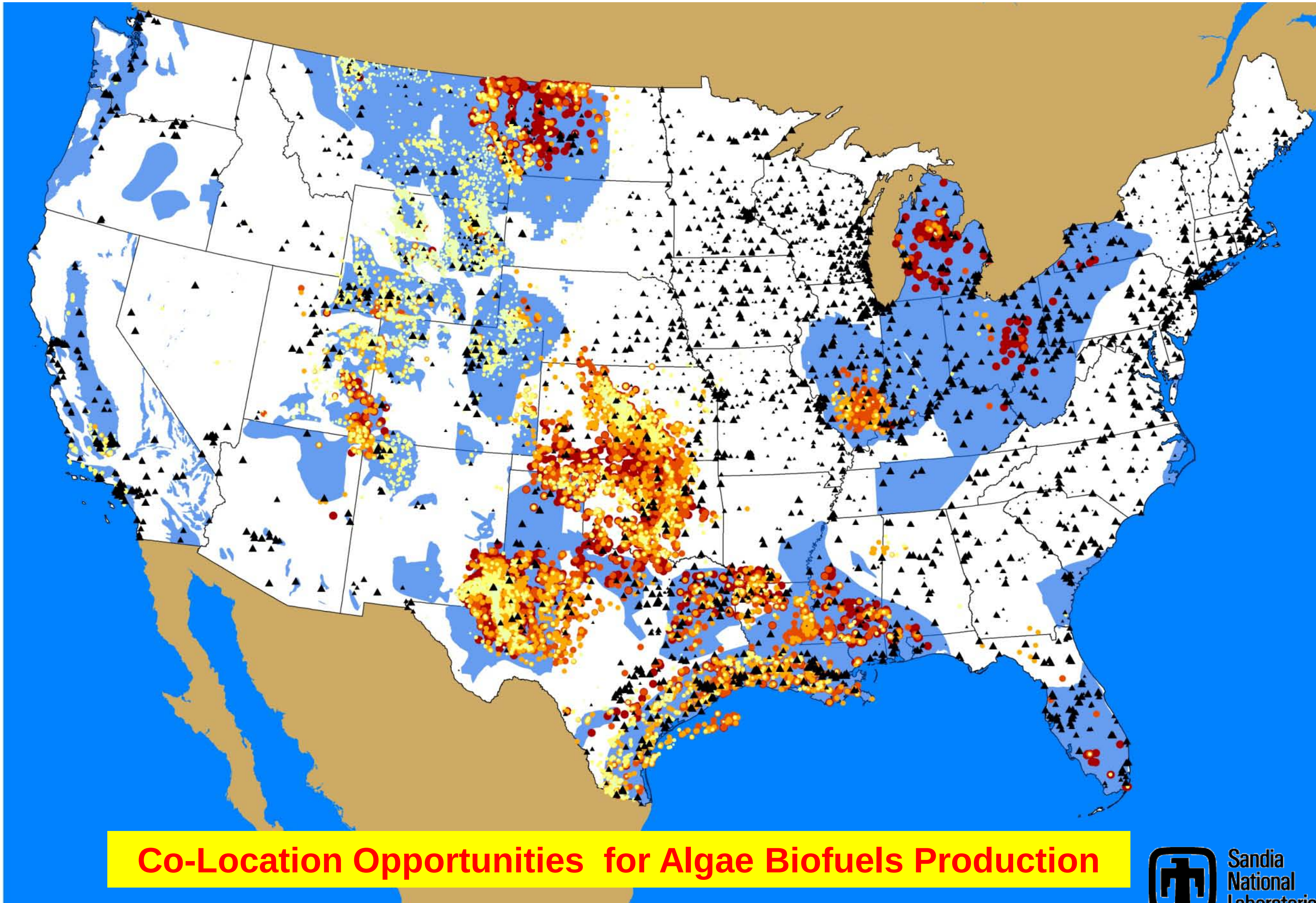
CO_2 Emitter and Non-Fresh Water* Resources

*(e.g., Wastewater, Produced Water, Saline Aquifers, Marine Water)



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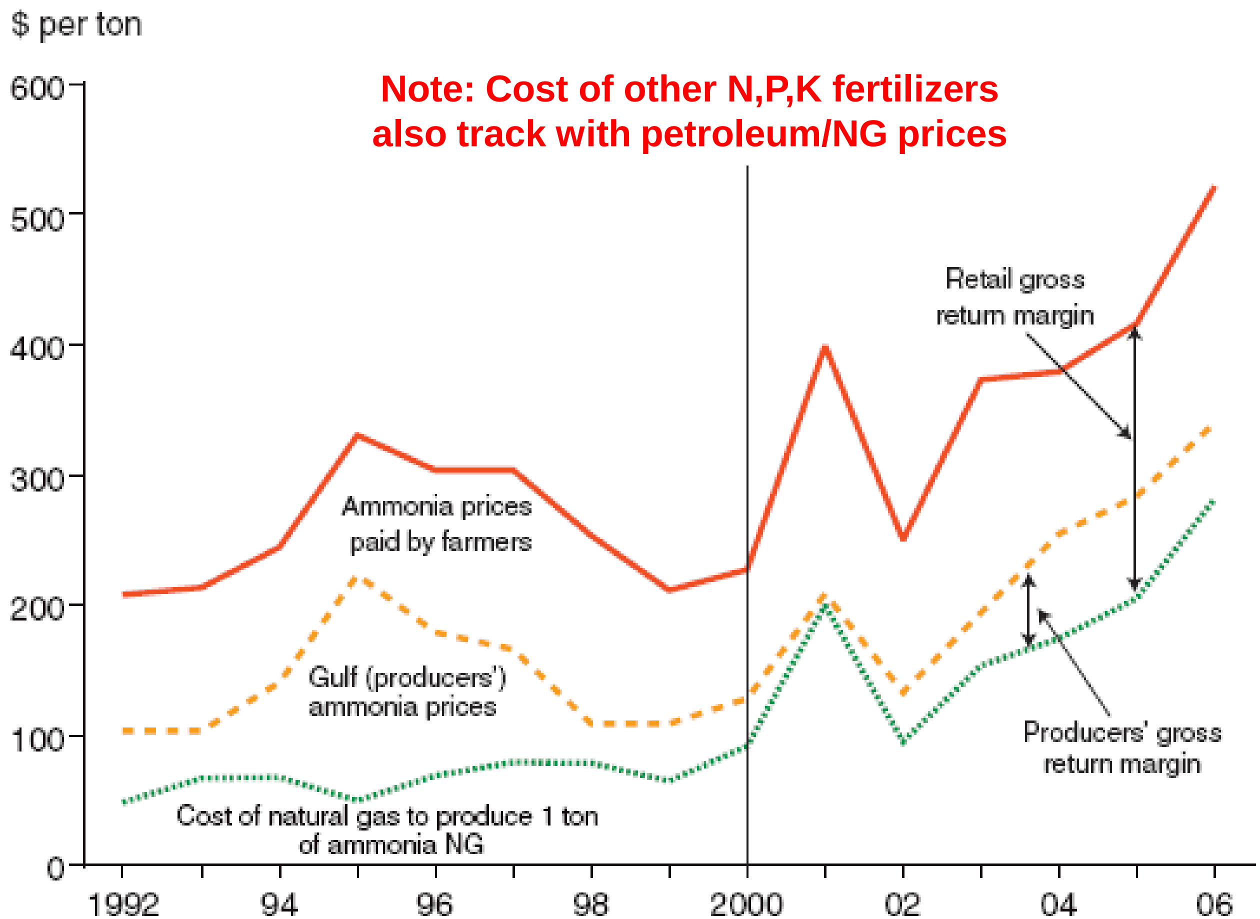
Other Nutrients (N, P, K) Needed for Algae Scale-up

- Subject to Increasing Costs Linked to Energy and Imported Fertilizer
- Need to recycle nutrients from waste streams for sustainable scale-up

U.S. ammonia prices and cost of U.S. natural gas to produce ammonia



Note: 32.7 mm Btu per ton of ammonia is used to compute the cost to produce 1 ton of ammonia.

Source: USDA, Economic Research Service using data on ammonia prices paid by farmers from NASS, and data on ammonia Gulf prices and natural gas prices from TFI (b).

Algae biomass

Nitrogen content ~5-8 %
Phosphorus content ~1%

Algae can require as much, or more, nitrogen per unit of biomass produced than other agricultural crops

Energy and GHG footprint from commercial fertilizers used for biofuel feedstock production reduces overall GHG benefit of the biofuel

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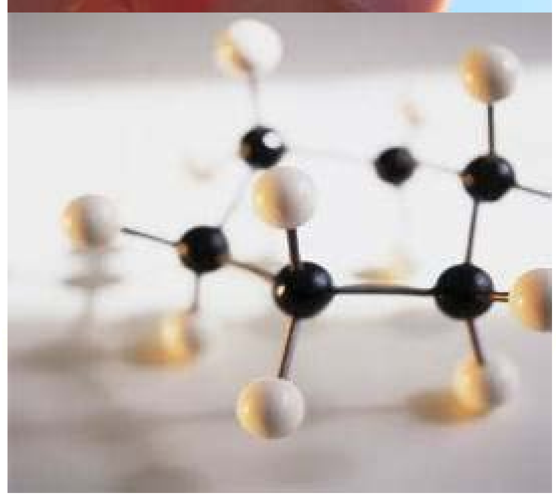
DOE/EERE Office of Biomass Program

Emerging Algae Biofuels Program and Investments






Successive Generations of Biofuels

Corn Ethanol

- Commercially available (no DOE research ongoing)
- Reduced GHG emissions
- Capped by RFS

Cellulosic Ethanol

- Focus of current DOE research
- Potential to lower GHG emissions 86%
- Uses biomass from waste and non-agricultural land

Advanced Biofuels

- DOE scoping effort in progress for **algae**, new biofuels & pathways
- Exploit opportunities to reduce environmental footprint
- Energy content and fuel economy similar to petroleum-based fuels

Future Needs for Biofuels and Bioenergy

Technology Advances

- Diverse feedstocks in all regions
- Flexible, bio-powered conversion
  - Mix of biochemical (advanced enzymes), thermochemical (pyrolysis, gasification, etc.), and other conversion technologies
- Increased yields and efficiency
- Lower production costs
- Efficient logistics and deployment
- Modular systems to reduce capital costs

Other National Benefits

- Sustainable domestic energy
- Strong economic growth (new technology markets and jobs)
- Positive impact on climate and air quality

New & High-Yield Feedstocks

- Energy crops
- Wastes
- **Algae**

Advanced Biofuels

- **Algal Based Biofuels**
- Higher Alcohols
- Green Gasoline
- Renewable Diesel
- Renewable Jet Fuel Formulations

Value-added Bioproducts/Coproducts

Carbon Mitigation

- Potential role in future carbon legislation

Stimulate/Leverage Scientific Progress

DOE Biofuels Sustainability Research Priorities

Biomass R&D Board Interagency Sustainability Working Group - Engaged in U.S. Government partnership to identify biofuels sustainability indicators

Indirect Land Use.- Developing models to help study international land use impact of domestic biofuels production and mandates

Climate Change - Conduct life cycle analysis (LCA) of biofuels production and use through a wide range of existing and future production pathways

Water - Conducting LCA of water demand for biofuel production (compares corn ethanol, sugarcane ethanol, and competing petroleum fuels)

Biodiversity – Study impact of biofuels industry growth on biodiversity and sensitive ecosystems

GIS Tools - Developing GIS tools to analyze current and future U.S. feedstocks, infrastructure availability, and economic and environmental sustainability … e.g., Knowledge Discovery Framework (KDF) (ORNL)
Resources assessment for algae production (PNNL)

Addressing sustainability challenges is critical to industry growth

Algal Biofuels Program Emerging

Launched with FY2009 and FY2010 Funding

Biomass Program

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. Some algal strains are capable of doubling their mass several times per day. In some cases, 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. NREL, Sandia, and other laboratories are also launching research into algal biofuels for private investors and programs within the Defense Advanced Research Projects Agency (DARPA) and Air Force Office of Scientific Research (AFOSR).

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).

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

Mitigation of CO_2:
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 make productive use of the CO_2 from power plants, biofuel facilities, and 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

Challenges to Commercialization

Algal biofuels are not economical to produce using the technology available today. Based on conservative estimates, algal biofuels produced in large volumes with current technology would cost more than $8 per gallon (in contrast to $4 per gallon for soybean oil today). Lowering this cost will require coordinated R&D across a wide range of technical sectors (listed at right) over the next 5 to 10 years. Although the technical challenges are significant, the broad public benefit of successfully commercializing algal biofuels warrants placing a high priority on the needed research. Particular attention must be paid to the engineering of sustainable microalgal systems and to the regulatory and environmental landscape.

Next Steps

To identify and prioritize R&D needs along the critical path to commercialization, DOE is holding an Algal Biofuels Workshop in Washington, D.C., in December 2008.

NREL and Sandia National Laboratories are working with DOE to plan and conduct this workshop, which will provide input for development of an Algal Biofuels Roadmap.

The roadmap will draw upon the expertise of a carefully balanced group of invited scientists and other experts in the various required disciplines (e.g., biology, systems and process engineering, modeling and analysis, algae cultivation, algal oil extraction and conversion, algal-based co-products, water and land use, policy and regulatory issues, etc.). Input from workshop participants will help define activities needed to resolve uncertainties associated with commercial-scale algal biofuel production. Upon completion of review and concurrence cycles, the resulting roadmap will be made available to the general scientific community in 2009. For updates as this process unfolds, please watch for news on our website: www.biofuels.energy.gov

R&D Focus Areas for Algal Biofuels

Basic Algal Biology

- Algae strain isolation and screening
- Genetics, genomics, strain improvement tools
- Photosynthesis and solar conversion efficiency
- Algae lipid productivity; biochemistry, and regulation of lipid accumulation

Process Research

- Algae mass cultivation
- Control of competitors, grazers, and pathogens
- System design and engineering
- Algae for wastewater treatment

Production and Integrated Process Scale Up

- Long term maintenance of desired strain in culture
- Hydrodynamics of mixing
- Evaluation of local water supply for algal cultivation
- CO_2 supply
- Harvesting technology
- Oil extraction technology
- Optimization of specific fuel production processes
- Analysis of algal biofuels for compliance with ASTM standards.

Economic Analysis

- Detailed process analysis
- Potential for value-added co-products
- Resource and siting analysis
- Environmental and social issues
- Environmental impact of large-scale algae farms
- Water usage and process water disposal
- Regulatory issues, especially cultivation of genetically modified algae
- Public awareness and acceptance

For additional information, please contact:

The EERE Information Center
(877) EERE-INF (337-3463)
www.eere.energy.gov/informationcenter

Visit our website at
www.biofuels.energy.gov

A Strong Energy Portfolio for a Strong America

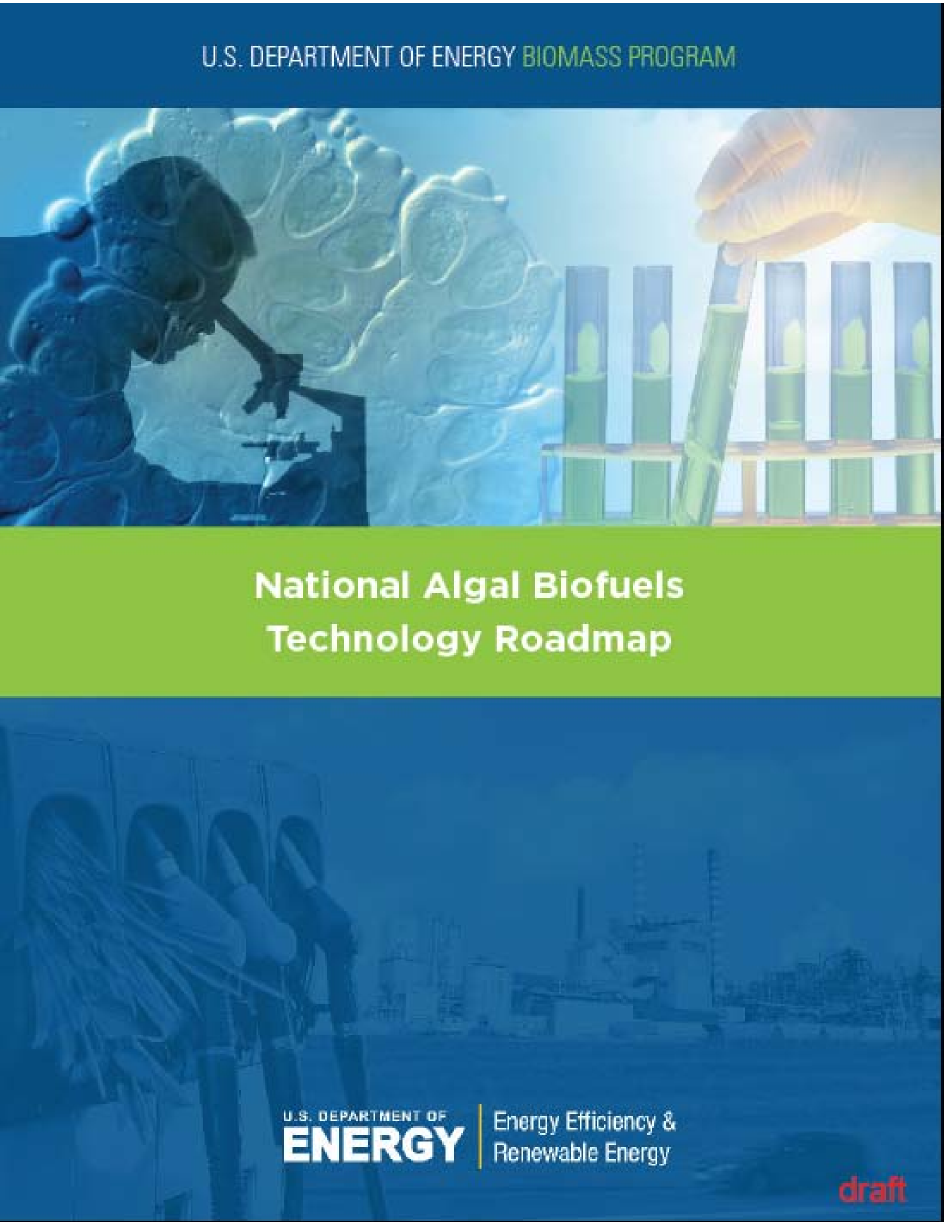
Energy efficiency and clean, renewable energy will mean a stronger economy, a cleaner environment, and greater energy independence for America. Working with a wide array of state, community, industry, and university partners, the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy invests in a diverse portfolio of energy technologies.

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

Growing America's Energy Future

National Algal Biofuels Technology Roadmap

Revised Final Draft Report in Review… To be Published Early-2010



Initiated : *Early-FY09*

Goal: *Identify needs, gaps, and fundamental and applied research needed to resolve uncertainties and reduce technical risks to enable and accelerate commercial-scale algal biofuel production. Scope of Roadmap includes:*

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

Recovery Act: Biofuels RD&D Projects

$480M Pilot & Demonstration-Scale Biorefineries

Validate technologies for integrated production of advanced biofuels, products, and power to enable private financing and replication;

DOE grant awards for refineries to be operational within 5 years:

- Two $25M pilot-scale project awards for **algae** (Algenol ; Solazyme)
- One $50M demonstration-scale project for **algae** (Sapphire)

$176M Commercial-Scale Biorefineries

Increase in funding for prior awards; two or more projects

Expedite construction; accelerate commissioning & start up

$110M Fundamental and Applied Research

$25M: Three existing DOE Bioenergy Research Centers and new, small-scale pilot plant/user facility for sustainability research

$35M: Advanced Research Consortium; infrastructure-compatible biofuels

$50M: **Algal Biofuels Consortium** to accelerate demonstration

… $44M awarded to Nat'l Alliance for Adv. Biofuels and Bioproducts (NAABB) Team

$20M Ethanol Infrastructure Research

Optimize flex-fuel vehicles operating on E85

Evaluate impacts of intermediate blends on conventional vehicles

Upgrade existing infrastructure for compatibility with E85

$13.5M Expand NREL Biochemical Pilot Plant

Expand pre-treatment options and capacity

Total: $799.5 million

DOE/EERE OBP Algae Consortium

Algal Biofuels Consortium FOA issued July 2009

- Purpose is to "accelerate technology development"
- ARRA-funded competitive solicitation for 3-year project funding

  … $44M awarded to NAABB team (announced Jan 13, 2010)

Primary objective – "develop cost effective algae-based biofuels that are competitive with petroleum counterparts"

Other guidance

- Focus on barriers from DOE's National Algal Biofuels Roadmap
- Not seeking to construct new facilities but leverage existing capabilities and resources
- Partnerships emphasized, because suite of technologies and capabilities is required
- Additional (non-ARRA) funds (~$35M) to be invested in algae biofuels research in FY2010 (details TBD)

Algal Biofuels Technology Challenge Areas

1. **Feedstock supply:** Strain development and cultivation
2. **Feedstock logistics:** Harvesting, dewatering, extraction
3. **Conversion/Production:** Accumulation and separation of intermediate feedstocks followed by synthesis of fuels and co-products
4. **Infrastructure:** Fuel testing and standardization
5. **Sustainable Practices:** Life Cycle and Techno-Economic analyses, siting and resources management

Summary

- Despite long-recognized potential, commercial scale-up of affordable and sustainable algal biofuels is yet to be realized;
- Fourteen years after the Aquatic Species Program, DOE/EERE is again investing in algae biofuels R&D;
- An updated algae roadmap effort was initiated in FY09 to provide objective update on technical status and R&D needs;
- $100M in competitive grant funding (ARRA) awarded by DOE to three cost-shared algae biofuel pilot scale (Algenol and Solazyme) and demonstration scale (Sapphire) Integrated Biorefinery (IBR) projects to:
  - validate advanced biofuels and bioproducts production technologies and processes in an integrated system;
  - provide data to enable private financing of commercial scale replications;

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Summary … continued

- $44M in competitive grant funding (ARRA) has been awarded by DOE to a cost-shared algae consortium team (NAABB) to pursue technical challenges and reduce risks identified in the algae roadmap;
- Additional FY2010 funding will be invested in algae biofuels research, and algae is being integrated into the DOE/EERE Biomass Program;
- Investments by DOE, other federal agencies, and private industry can be expected to yield advances in algae biofuels over the next 3-5 years;
- Major challenges:
  - reduce costs to enable affordable & competitive biofuels from algae
  - increase reliable productivity *(biomass and/or extractable oil)*
  - provide improved systems and processes operations & performance
  - provide environmental benefits and avoid adverse scale-up impacts.
- Major factor: Future price and availability of petroleum

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Thank You !

Questions ?