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ENG 300

Introduction to Biofuels

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Energy, Resources, and Systems Analysis Center

May 7, 2009

Sandia is a multiprogram laboratory operated by Sandia Corporation, a LockheedMartin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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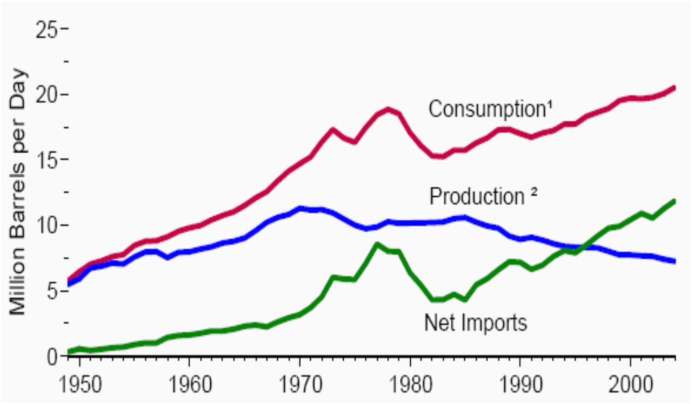
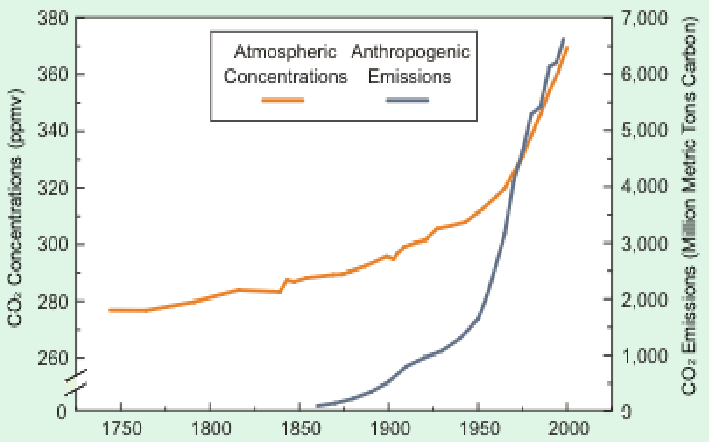
We Are Facing Unprecedented Transportation Fuels Challenges

- Largest end use of energy by sector
- 97% of transportation energy comes from petroleum
- Two-thirds of petroleum is used for transportation -- 60% for ground





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

- Gasoline and diesel both produce about 20 pounds of CO_2 per gallon
  - 7 tons of carbon/vehicle-year
- Transportation presents a unique challenge because onboard sequestration is not credible

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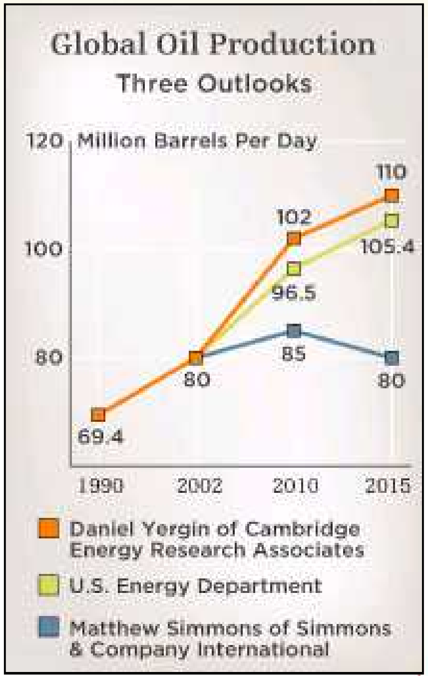
Biofuels Interest & Motivation

- **Energy Security … Heavy U.S. dependence on petroleum imports**
  - Oil imports of ~10-M bbl/day (150+ B-gal/yr)
    … two thirds for transportation fuels
  - Subject to supply disruption from volatile regions
  - Represents $400(+/-) B/yr burden on U.S. economy
    … supports interests hostile to US
  - Increasing competition (China, India, etc.)
    & price volatility for limited global supplies
  - Inevitability of "Peak Oil"
    … timing is uncertain, but long-term eventuality is not



- **Desire for Reduced GHG Footprint**
  - Climate Change concerns make renewable biomass-based fuels attractive
  - Potential for displacing fossil carbon fuels with more carbon-neutral fuels
  - Energy balance depends on systems and processes… not all good !
- **Energy-Water-Environment-Economy Interdependencies**
  - Need solutions to affordable & *sustainable* scale-up
  - Need to ID best paths to avoid or minimize adverse impacts

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Vision for Sustainable Transition

from Petroleum to Biomass Based Fuels and Products

Emerging Biomass-Based Energy & Products Industries

Biomass Feedstocks

- Forestry Thinnings
- Agricultural Crops
  - Starch crops
  - Oil crops
  - Sugar crops
  - Cellulosic energy crops (perennial grasses & trees)
- Ag & Forest Residues
- Animal Wastes
- Municipal Solid Waste
- Algae

Conversion Processes

- Steam/Other Pretreatment
- Enzymatic Fermentation
- Gas/liquid Fermentation
- Acid Hydrolysis/Fermentation
- Transesterification (oils)
- Gasification / Synthesis
- Pyrolysis / Synthesis-Refining
- Combustion
- Co-firing

USES

Fuels:
- Ethanol
- BioDiesel
- Synthesized Diesel
- Synthesized Gasoline
- Biogas (Methane)
- Numerous Other

Power:
- Electricity
- Heat

Chemicals
- Plastics
- Solvents
- Chemical Intermediates
- Phenolics
- Adhesives
- Furfural
- Fatty acids
- Acetic Acid
- Carbon black
- Paints
- Dyes, Pigments, and Ink
- Detergents
- Lubricants
- Etc.

Food and Feed and Fiber

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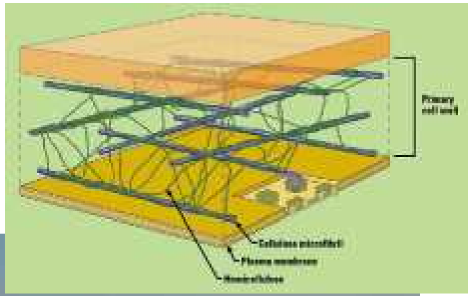
- The nation pays a high price for oil
  - Critical national security issues
  - Unprecedented environmental harm
  - Dwindling supply and price fluctuations

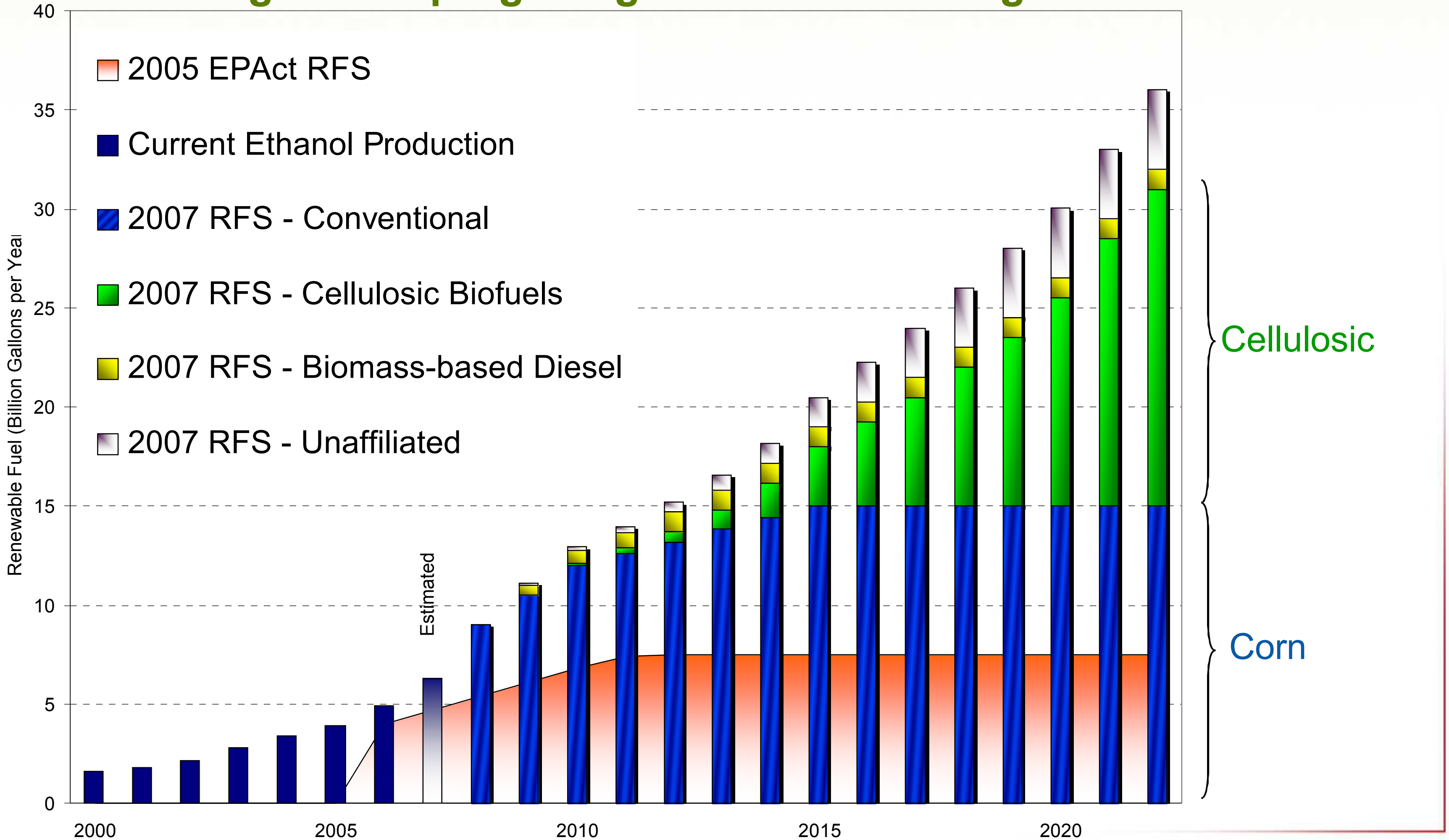
Energy from biomass holds sustainable energy promise, however:



- Current starch, sugar, and oil crop based feedstocks and biofuels (1st-Gen biofuels) have sustainable scale-up issues and/or impacts on other food/feed/fiber markets
- Current cellulosic ethanol (2nd-Gen biofuel) production is expensive and energy intensive
- Revolutionary breakthroughs are needed to create energy-efficient, cost-effective cellulosic biofuel
- Algae has high potential for longer-term (3rd-Gen) biofuels, but faces major technical and economic challenges for commercial scale-up.

Current U.S. Policy Driver: EISA Renewable Fuel Standard

36 billion gallons of renewable fuels by 2022
DOE longer term program goals tied to this legislation



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

Research Drivers – Energy Security and Environmental Concerns

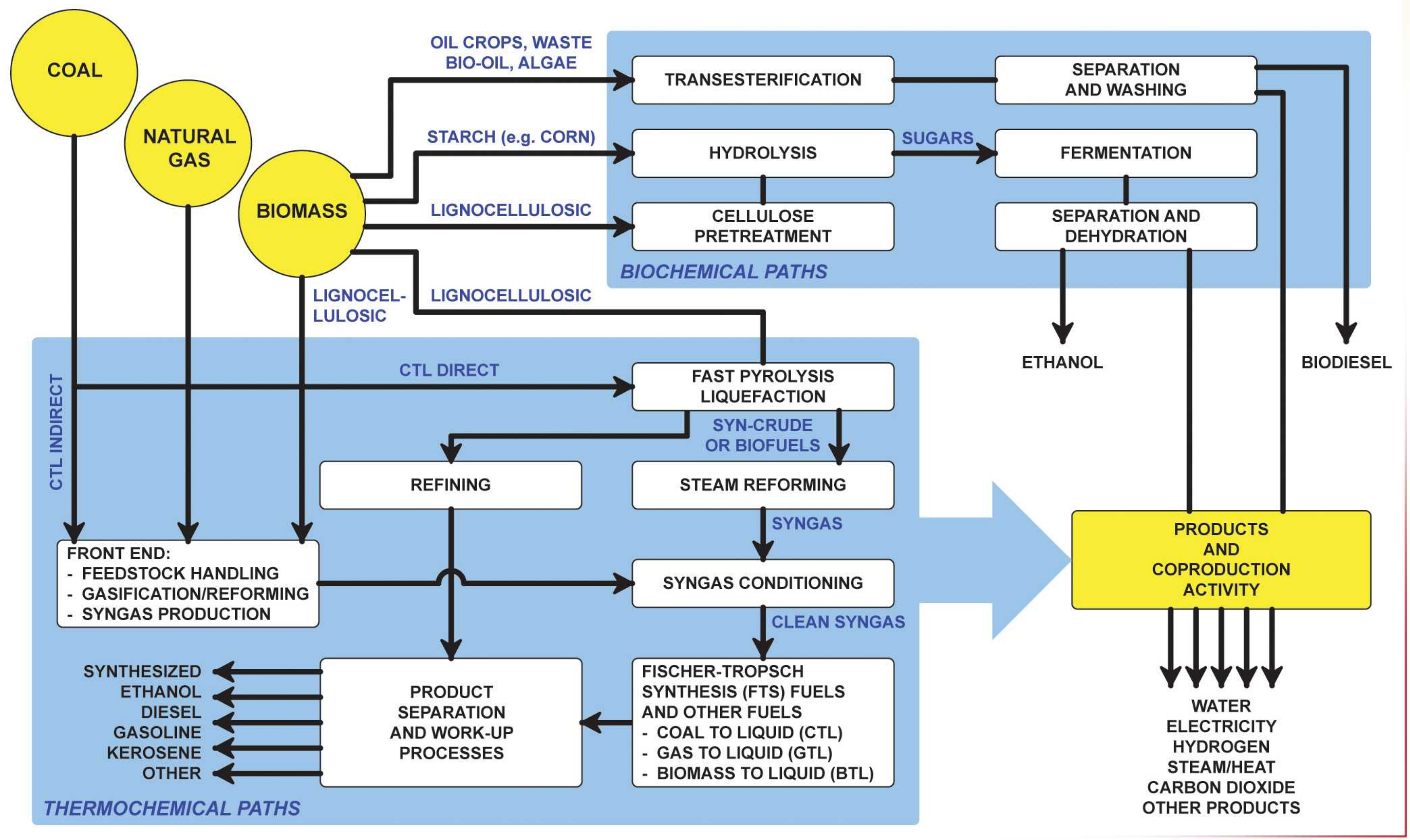
Conclusions:

- Changes in the feedstocks from which fuels are produced are likely to occur in this century
- Future fuel-supply feedstocks and technologies must be sustainable, as well as affordable and scaleable
- Novel catalytic technologies will be required for the production of fuels
- Increased end-use efficiencies will be required to help reduce fuel demand

Implications:

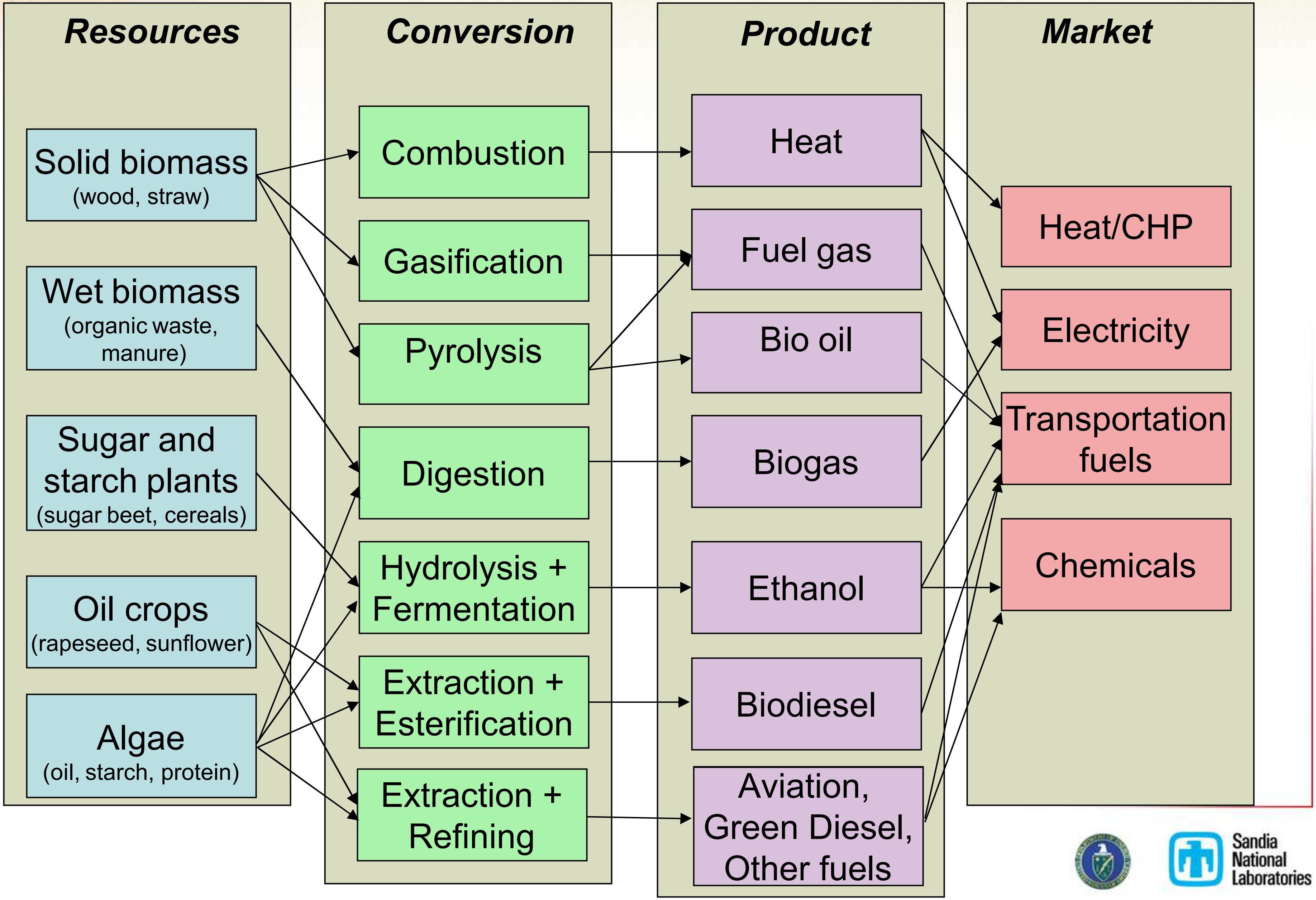
- Research should be directed at developing a fundamental understanding of how future alternative fuel feedstocks (biomass, oil shale, other) can be converted to fuels efficiently w/ minimal adverse environmental impacts
- Basic research aimed at understanding catalyst structure and catalytic phenomena will contribute to the knowledge base used to guide the discovery and development of new catalysts
- Basic and applied R&D needed on enabling sustainable and affordable biomass-based feedstocks, fuels, and other co-products

Feedstocks and Pathways for Several Transportation Fuel Alternatives



Adapted from: EIA 2006; Huber, et.al., 2006

Biomass Interconversion Pathways



Other Emerging Factors for Biofuels

A Growing Awareness of Sustainability Issues… e.g., water

Water Use
by Ethanol Plants

Potential Challenges

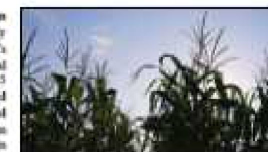
Institute for Agriculture and Trade Policy

THE NATIONAL ACADEMIES

REPORT IN BRIEF

October 2007

Water Implications of Biofuels Production in the United States



Types of Biofuels

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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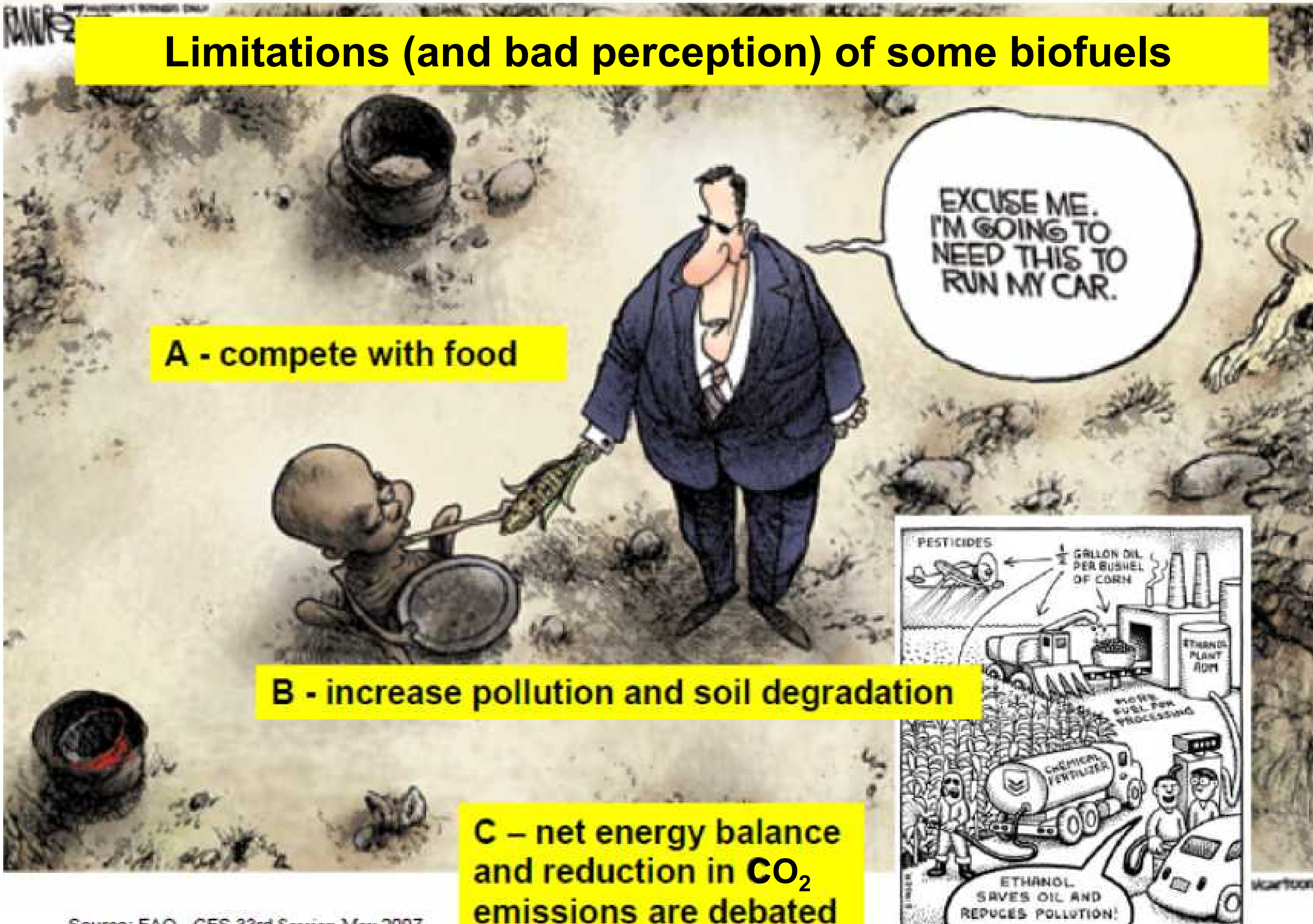
Other Emerging Factors for Biofuels

More Sustainability Issues… food & feed vs. fuel

Limitations (and bad perception) of some biofuels



A - compete with food

B - increase pollution and soil degradation

C – net energy balance and reduction in CO_2 emissions are debated

Source: FAO - CFS 33rd Session-May 2007

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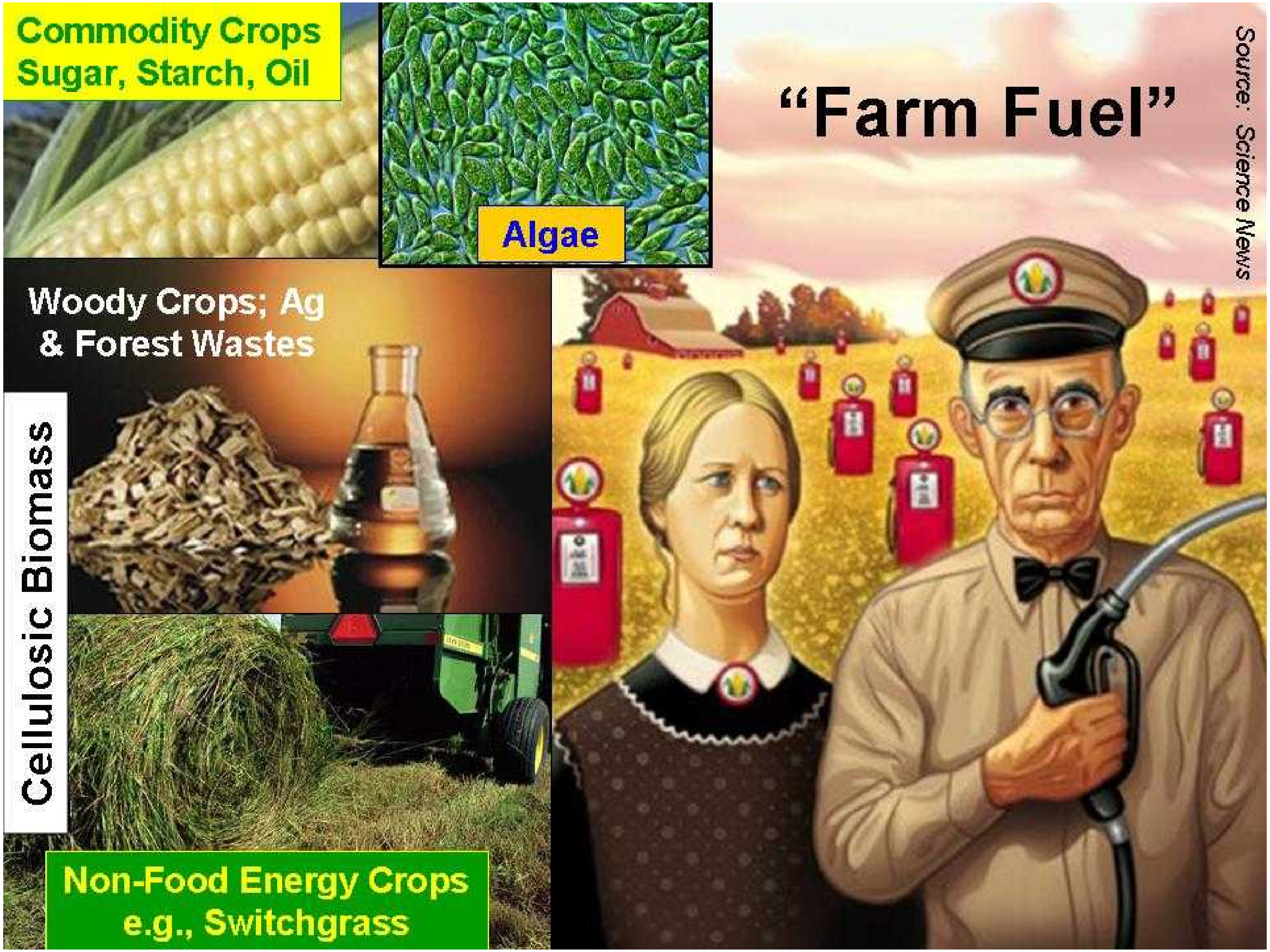
Biofuels Challenge: Sustainable Scale-Up



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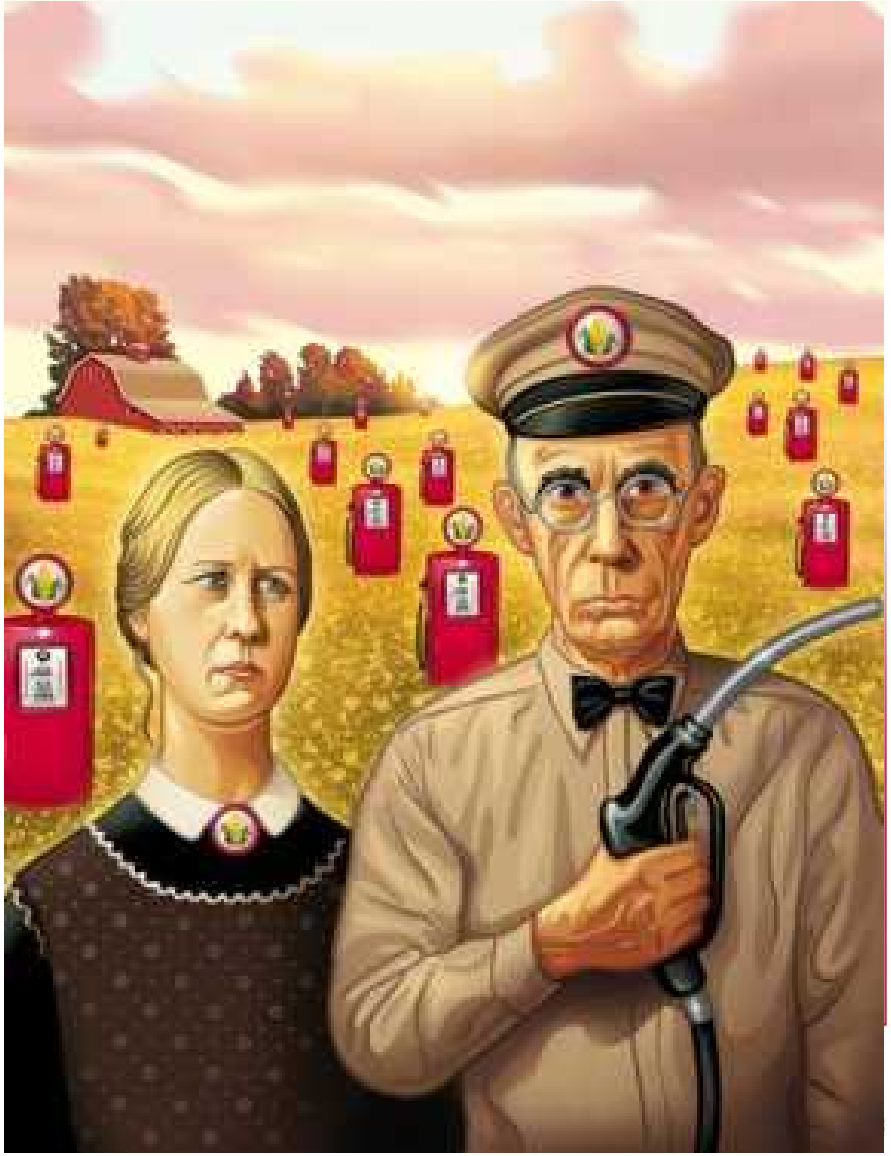
1^{st}-Generation Biofuels
Production Challenges

- Fuel ethanol in U.S. produced from starch grain crops (e.g., corn)
- Biodiesel in U.S. produced from waste animal & vegetable oils and commodity oil crops (e.g., soy)
- Tax breaks provided for both
- Fuel ethanol is on track to reach 15-billion gal/yr production
- Biodiesel production limited to less that 1-B gal/yr by lack of affordable feedstocks
- Commodity crop based EtOH and biodiesel are linked to other agricultural food and feed markets, making them subject to the food vs. fuel debate
- Both fuel EtOH and biodiesel lack seamless fungibility with the conventional hydrocarbon fuel infrastructure (i.e., requires blending and/or modifications to distribution system and vehicles)
- Neither fuel can meet certification for aviation fuel use



2^{nd}-Generation Biofuels
(e.g., Cellulosic Ethanol) Production Challenges

Projected Benefits

- Improved Energy Balance (vs. 1^{st} Gen)
- Reduced GHG footprint (vs. 1^{st} Gen)
- More sustainable feedstock and biofuel production scale-up (vs. 1^{st} Gen)

What's Needed

- Mandate: 16-Billion Gal/Yr by 2022 (per ESIA 2007 RFS)
- Must develop alternative sources of feedstocks and processing to meet Federal goals
- Ethanol derived from cellulosic material is the most viable alternative
  - Cost reductions needed for commercial viability

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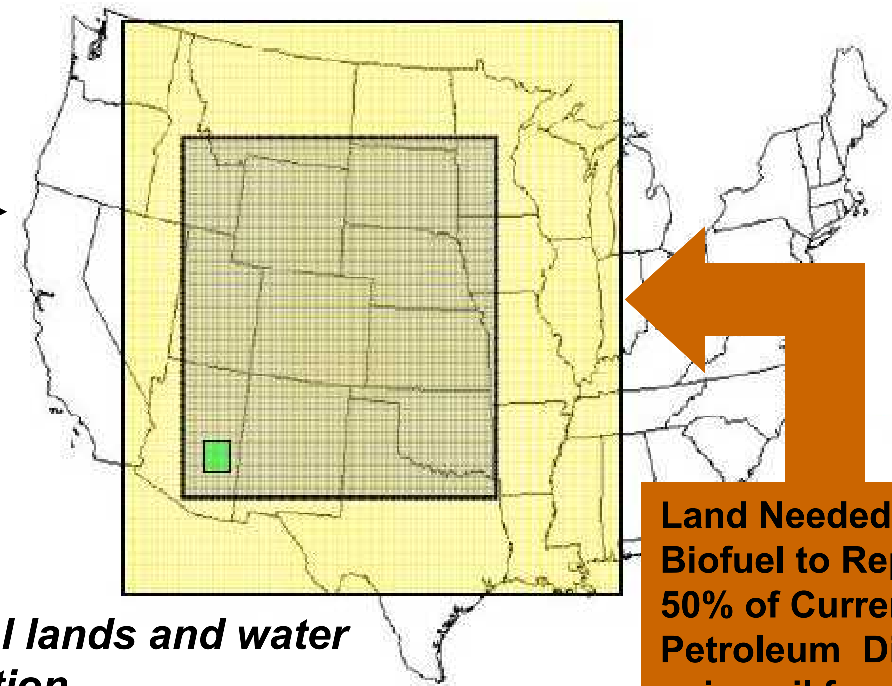
3rd-Generation (e.g., Algae-Based) Biofuels

Potential advantages over 1st and 2nd generation feedstocks and biofuels as an alternative to petroleum-based fuels.

Gallons of Oil per Acre per Year (approximate)	
Corn	18
Soybeans	48
Safflower	83
Sunflower	102
Rapeseed	127
Oil Palm	635
Micro Algae	2000-10000



Land Needed for Biofuel to Replace 50% of Current Petroleum Diesel using oil from:
Corn
Soybean
Algae

- ***Need not compete with agricultural lands and water required for food and feed production***
- ***Can potentially reduce deforestation (Science, 2008)***
  … indirect land use impacts
- ***Can use non-fresh water… Avoids fresh water depletion***
- ***Produces higher energy-content fuels that are fungible with current hydrocarbon fuel distribution and end-use system***
- ***Higher photosynthetic efficiency than terrestrial energy crops***
  … more effectively captures and reuses CO2

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Biofuels: Current Status

- **Bio-derived liquid fuels address two significant national risks:**

  1) Dependence on foreign oil

  → Biofuels can be produced domestically; Leverage existing hydrocarbon fuel distribution/use infrastructure

  2) Climate impact of CO_2 emissions from fossil fuels

  → Biofuels are potentially carbon neutral; Capture and re-use carbon from atmospheric CO_2

- **Current pathways for more biomass-based fuels (1st & 2nd Generation):**
  - Ethanol (e.g., from corn seed wet/dry milling, other starch/sugar crops) : ~ 9 billion gal produced in 2008
    - Compare to 140 billion gal/yr for current petroleum gasoline fuel blend use in U.S.
  - Biodiesel (e.g., from soy beans, waste oils, etc.): ~700 million gal produced in 2008
    - Compare to 62 billion gal/yr for current petroleum diesel fuel use in U.S.
    - Potential market for up to 1-3 billion gal/yr domestic production from vegetable oils with room for further enhancements
  - Lignocellulosic ethanol … not yet commercial, research and pilot scale plants
    - USDA/DOE: ~1.3 billion tons per year available for conversion
    - Typical yield: 65-100 gallons/ton (dry weight biomass) ; 5-10 tons dry weight biomass per acre
  - Biohydrogen from microorganisms … research, not commercial
  - Fuels and/or intermediates (alkanes, alcohols, syngas) derived from processing of biomass via gasification, pyrolysis, solar heating … not yet commercial; research and pilot scale plants
  - Other high-value fuels from bio-oil sources in development (e.g. DARPA): renewable aviation & green diesel

- **TAG oil and other hydrocarbon-like feedstocks & fuels from algae & other microbes:**
  - Autotrophic (photobioreactor) production based on photosynthesis with CO_2
  - Heterotrophic (industrial bioreactor or waste treatment) production based on organic carbon sources
  - Various fuels (biodiesel, green diesel, aviation, etc.), co-products (animal feed, fertilizer, biogas, etc.), and co-services (carbon capture & re-use, nutrient extraction & re-use from contaminated waters) … research & pilot plants… not commercial

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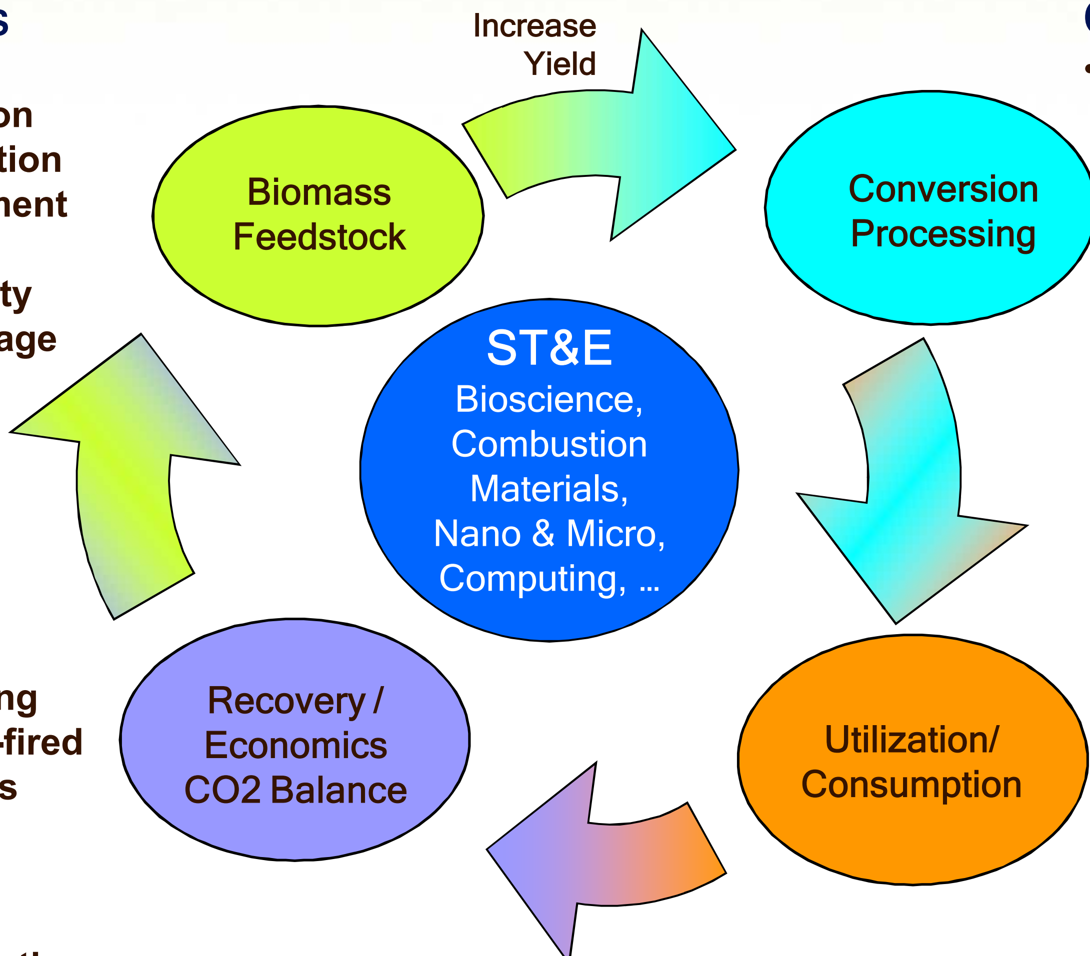
Sandia's Biofuels Strategy:
A Systems Approach

Challenges
- Biomass
    - Production
    - Optimization
    - Pretreatment
    - Scale-up
- Sustainability
    - Water usage

Challenges
- Biomass processing
    - Catalysis
    - Thermochemical
    - Biochemical
    - Scale-up
    - Microbial communities



Challenges
- Carbon Implications
  e.g. Co-siting with Coal-fired generators
- Biomass production
  e.g. Transportation costs & Water availability

Challenges
- Engine design
- Fuel Distribution
- Fuel Storage
- Materials Compatibility
- US Infrastructure Implications (Systems)

Our program is focused on two primary sources of biomass: cellulose & algae

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Sandia Bioenergy-Related Activities

Monsanto CRADA

Microalgal Biodiesel Feedstock Improvement by Metabolic Engineering LDRD

From Algae to Oilgae

LDRD

Systems Dynamics Analyses

GM Biofuels Modeling

Minnesota Biobusiness Alliance

& Others

Integrated Energy-Water Assessment and Planning LDRD

NM TRC Dairy waste streams to energy

JP8 Biofuel DARPA BAA06-43 UOP Project Team

DOE/EERE-OBP* National Algae Biofuels Roadmap

West Coast Biorefinery

Joint Bioenergy Institute (JBEI)

DOE-Funded Team LBNL,LLNL,SNL,others

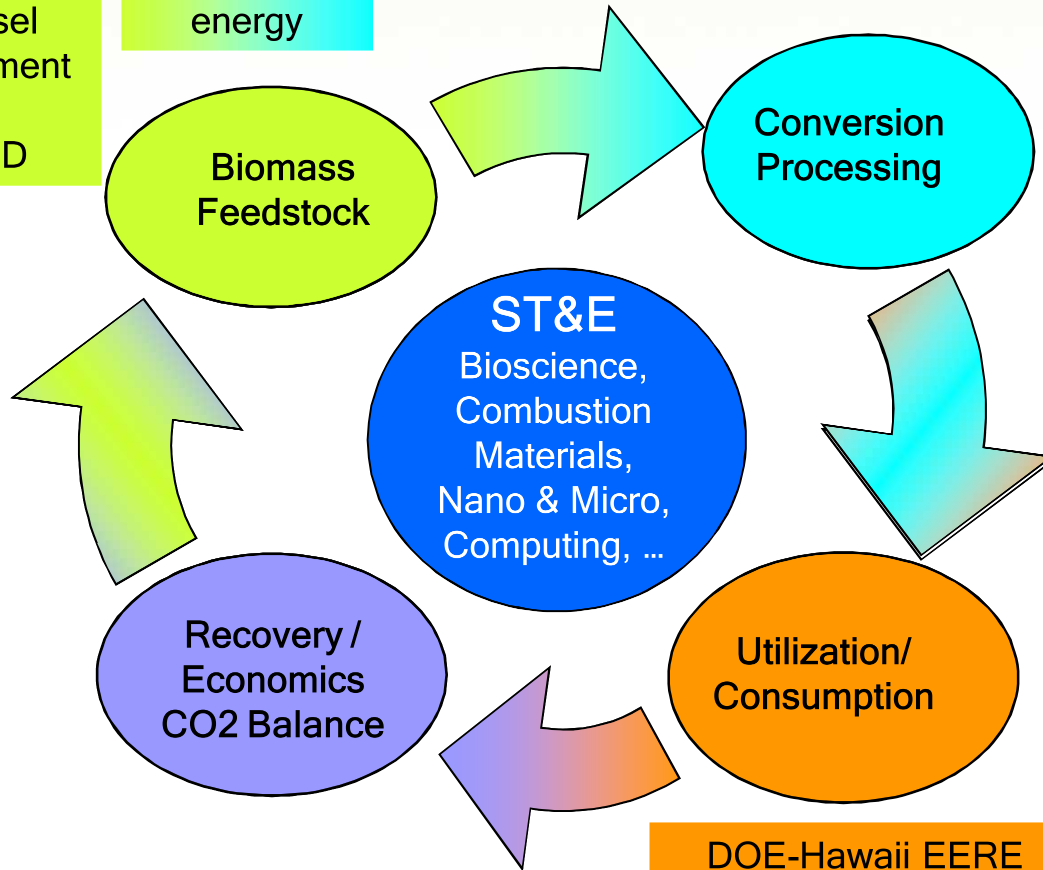
DSM International

Biomass to Bioenergy: Protein & Metabolic Engineering LDRD

Breakdown of Lignocellulose Via Mixed-Microbes LDRD

Enhanced Ethanol from 5-Carbon Sugars LDRD

Efficient, Integrated Cellulosic Biorefineries LDRD



DOE-Hawaii EERE Initiative

Advanced Fuels Lab

DOE FreedomCar

Advanced Engine & Combustion R&D and Testing

* Draft Algae Roadmap Report currently in progress

Cellulosic Biofuels Initiative

DOE Office of Science

Department of Energy - Energy Department Selects Three Bioenergy Research Centers for $375 Million in Federal Funding

Press Releases
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June 26, 2007

Energy Department Selects Three Bioenergy Research Centers for $375 Million in Federal Funding

Basic Genomics Research Furthers President Bush's Plan to Reduce Gasoline Usage 20 Percent in Ten Year

WASHINGTON, DC – U. S. Department of Energy (DOE) Secretary Samuel W. Bodman today announced that DOE will invest up to $375 million in three new Bioenergy Research Centers that will be located in Oak Ridge, Tennessee; Madison, Wisconsin; and near Berkeley, California. The Centers are intended to accelerate basic research in the development of cellulosic ethanol and other biofuels, advancing President Bush's Twenty in Ten Initiative, which seeks to reduce U.S. gasoline consumption by 20 percent within ten years through increased efficiency and diversification of clean energy sources. The Department plans to fund the Centers for the first five years of operation (Fiscal Years 2008-2013).

"These Centers will provide the transformational science needed for bioenergy breakthroughs to advance President Bush's goal of making cellulosic ethanol cost-competitive with gasoline by 2012, and assist in reducing America's gasoline consumption by 20

News

University of Maryland Wins Communications Contest at Department of Energy's 2007 Solar Decathlon

German University Wins Architecture Contest in the Department of Energy's Third Solar Decathlon

Opening Ceremony 2007 Solar Decathlon

DOE Office of Science Publishes Update of Landmark Plan: "Facilities for the Future of Science: A Twenty-Year Outlook"

Related Links

Bio Centers Announcement at the National Press Club

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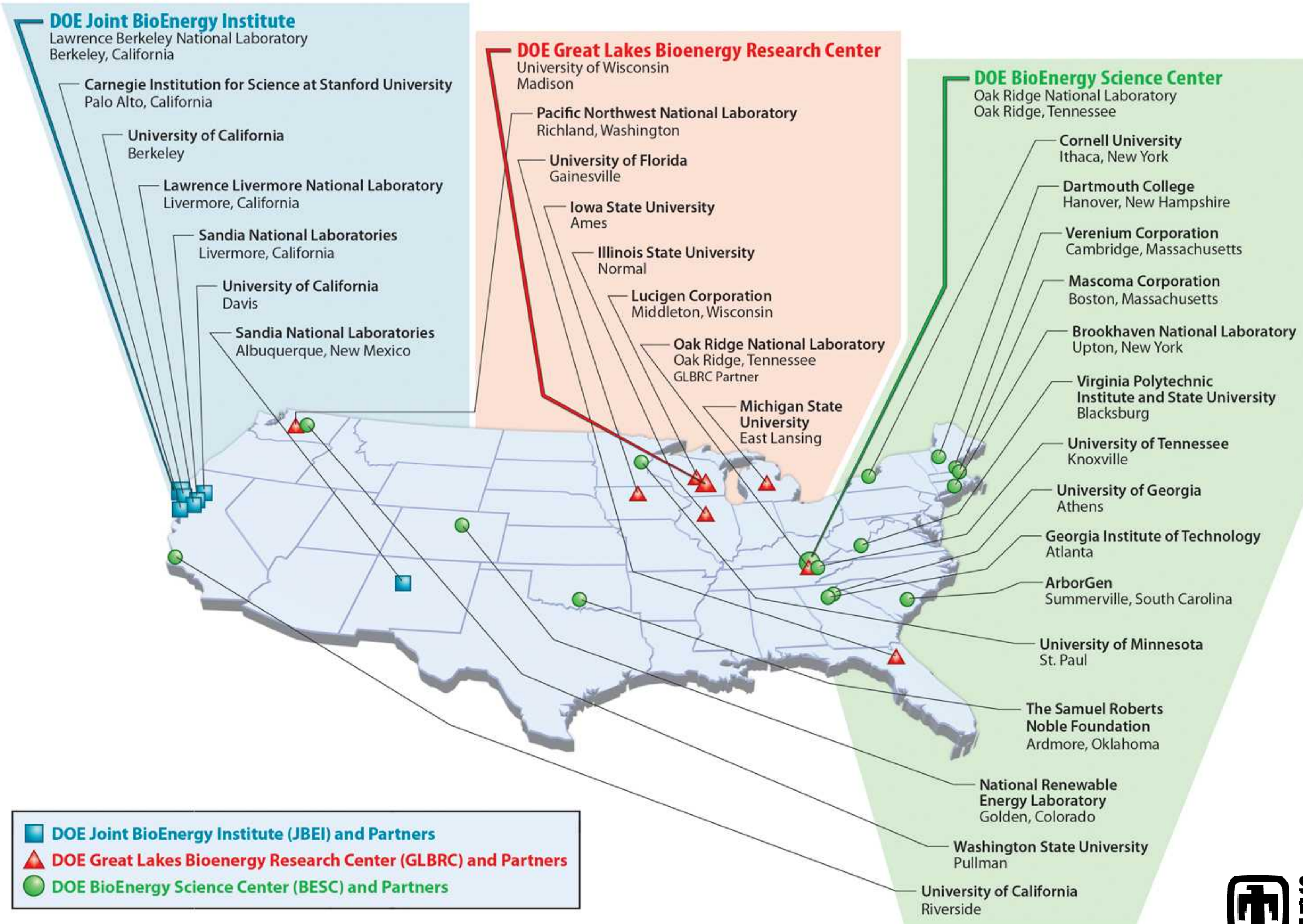
DOE Office of Science

BioEnergy Research Centers



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The Joint BioEnergy Institute

The JBEI Mission

- Develop alternative transportation fuels to meet future demands while reducing greenhouse gas emissions
- Pursue the scientific foundations for comprehensive, integrated research in biology relevant to energy production
- Provide the tools for cost effective production of biofuels
- Transfer JBEI inventions to the private sector for commercialization

BERKELEY LAB

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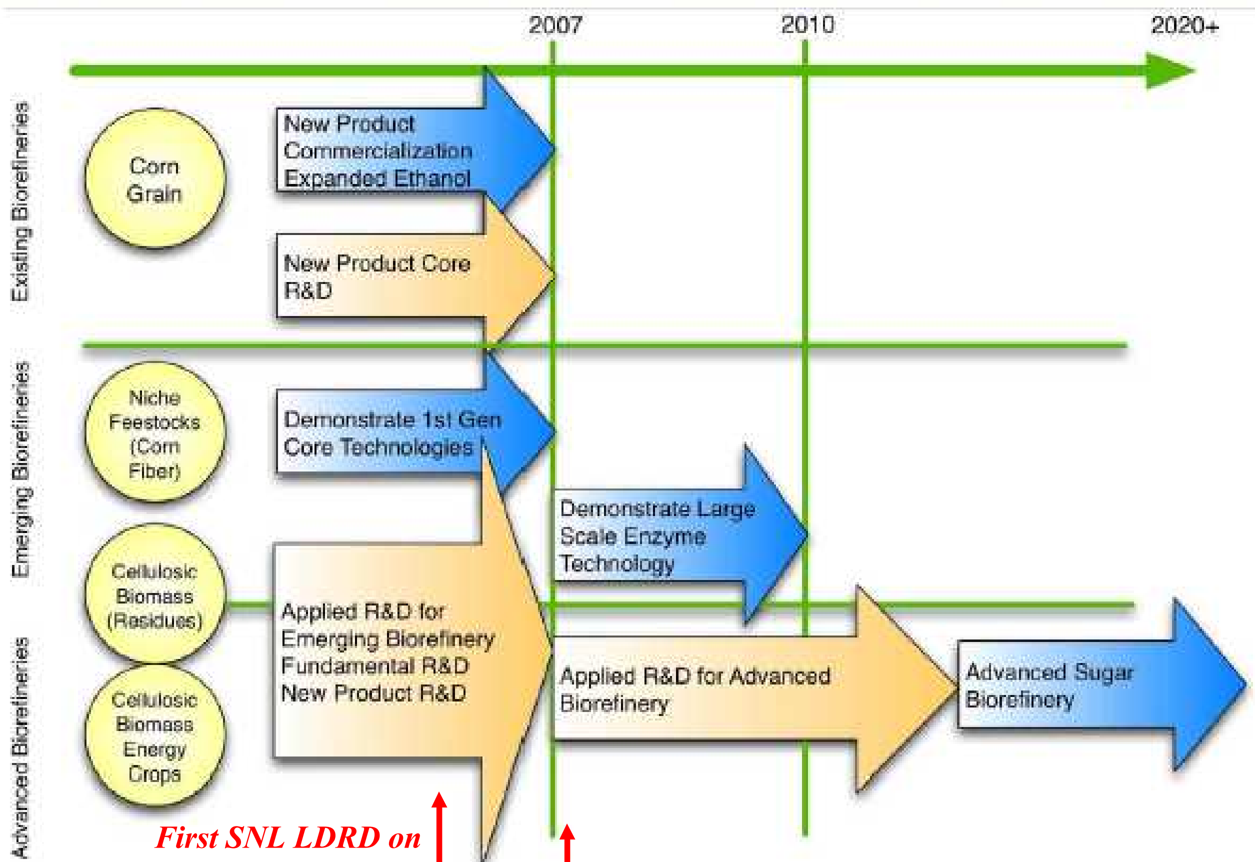
Biomass to Bioenergy

Lignocellulosic Ethanol: Enabling Consolidated Bioprocessing

DOE Strategic Vision for Lignocellulosic Ethanol:



First SNL LDRD on Cellulosic Ethanol

JBEI Awarded, West Coast Biorefinery, DSM

Multiple LDRDs funded on bioenergy, Mansanto CRADA

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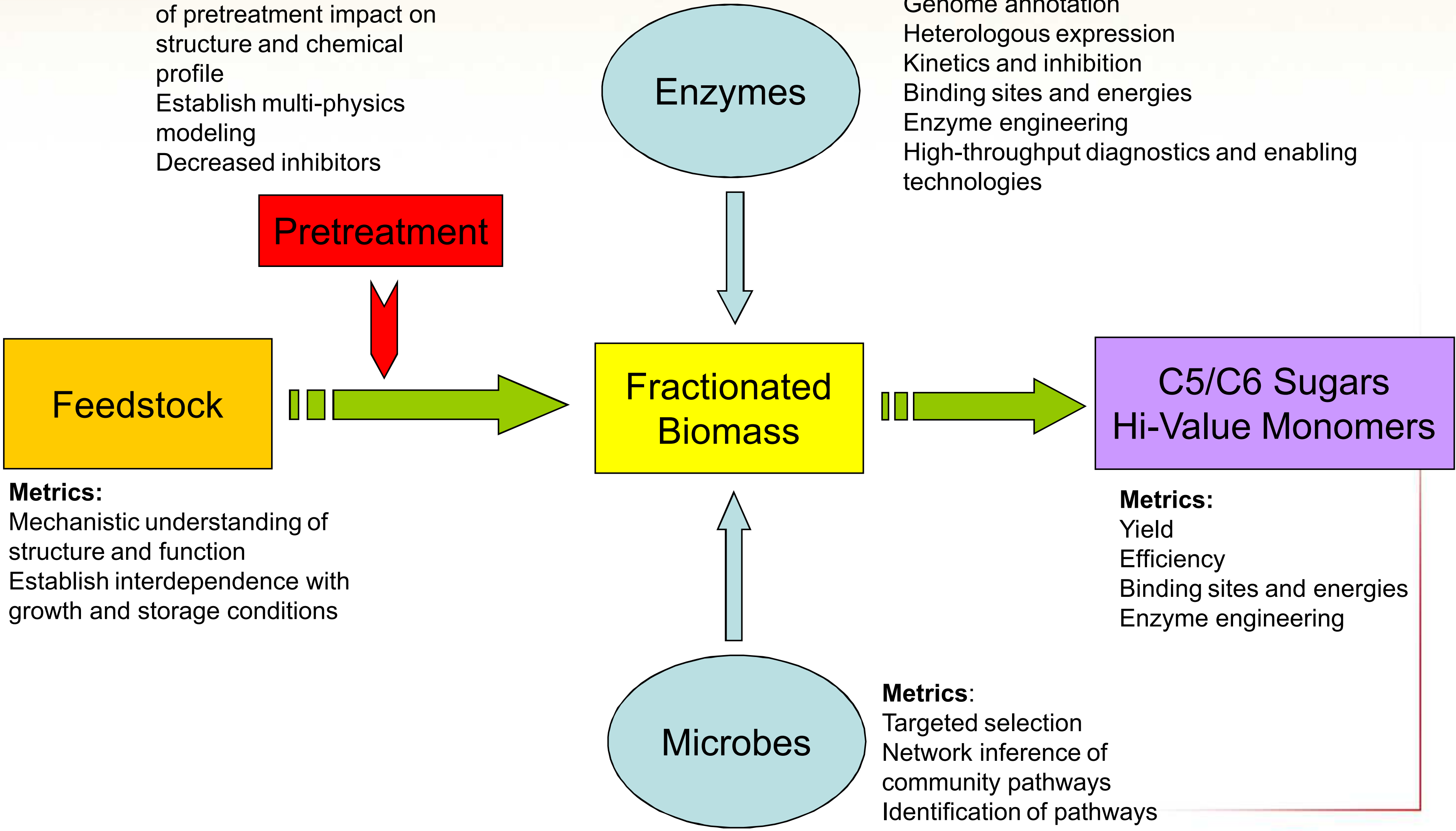
Cellulosic Biomass Processing Flow



Metrics:
Mechanistic understanding of pretreatment impact on structure and chemical profile
Establish multi-physics modeling
Decreased inhibitors

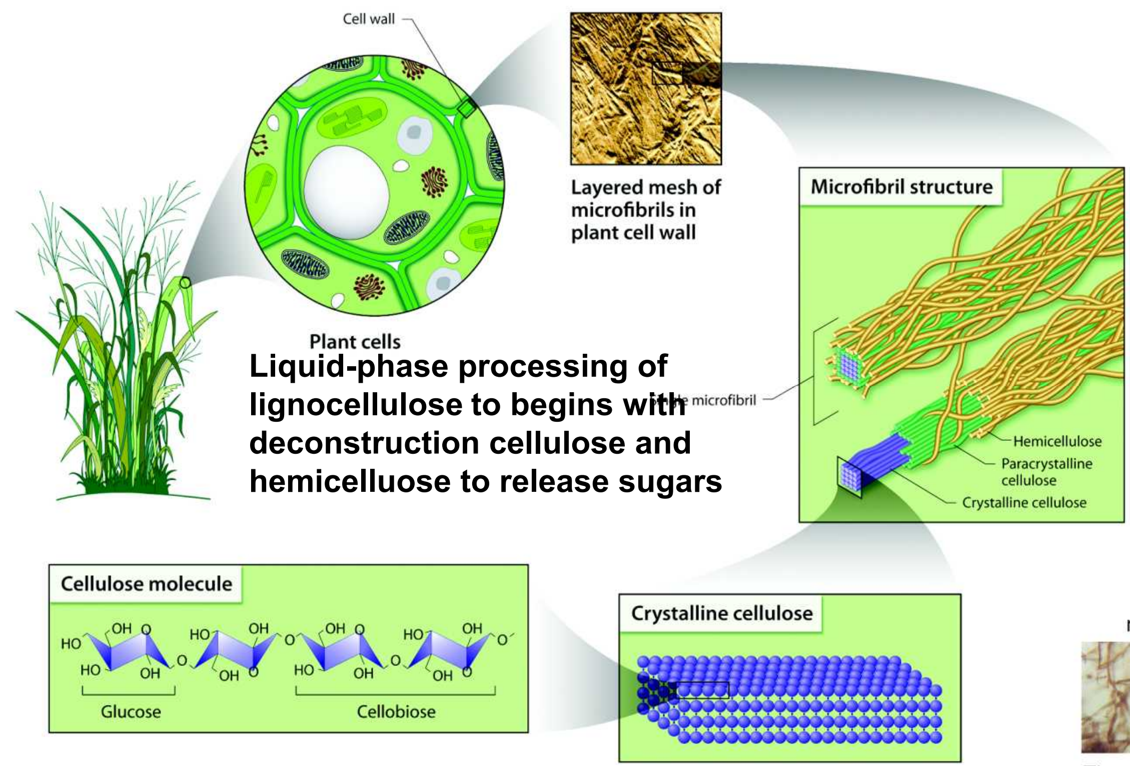
Metrics:
Library development
Genome annotation
Heterologous expression
Kinetics and inhibition
Binding sites and energies
Enzyme engineering
High-throughput diagnostics and enabling technologies

Metrics:
Mechanistic understanding of structure and function
Establish interdependence with growth and storage conditions

Metrics:
Yield
Efficiency
Binding sites and energies
Enzyme engineering

Metrics:
Targeted selection
Network inference of community pathways
Identification of pathways
Isolation of key enzymes
Genome annotation

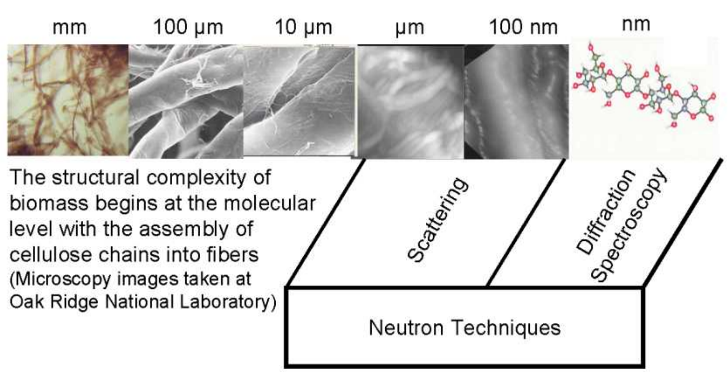
Advanced Catalysts for Conversion of Biologically-Derived Feedstocks to Fuels



Liquid-phase processing of lignocellulose to begins with deconstruction cellulose and hemicelluose to release sugars

Biomass can be converted to fuels by:

- **Pyrolysis – complex liquid products requiring further processing**
- **Gasification – produces CO/H_2 that can be converted further to diesel**
- **Deconstruction – produces sugars that can be converted to fuels by enzymatic or non-enzymatic catalysts**



The structural complexity of biomass begins at the molecular level with the assembly of cellulose chains into fibers (Microscopy images taken at Oak Ridge National Laboratory)

Pretreatment Summary
(combined with enzymatic hydrolysis)

Pretreatment	Conditions	Total Process Yield	Disadvantages
Ionic Liquids	Temp - 90-140 °C	Glucose ~ 75-90% Xylose - TBD%	Expensive
Ammonia Fiber Explosion	5-15% Ammonia; Temp - 150-180 °C; pH - 9-11	Glucose - 89% Xylose - 94%	Must recycle ammonia stream; sugar degradation as a function of temperature and time
Organosolv	Hot aqueous ethanol, catalysts	Glucose - 91% Xylose - 94%	Expensive; Handling requirements
Dilute Acid	Temp - 140-200 °C; pH - 2-4; Time - 20-60 minutes	Glucose - 91% Xylose - 90%	Unwanted inhibitory byproducts; capitalization cost
Hydrothermolysis	Temp - 200-230 °C; time - 15 min.; pH - above 4-5; Pressure - 350 - 400 psig	Glucose - 88% Xylose - 100%	Not efficient at softwood degradation

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R&D Opportunities:
Cellulosic Material Characterization & Pretreatment

- Innovative solvents with enhanced solubilization properties of all three major biomass constituents

- Establish computational modeling activity around biomass pretreatment beyond simple kinetics

- High-throughput, combinatorial approaches to discovery

- Establish fundamental, science-based understanding of biomass in different environments
  - Tie-in to multi-scale modeling coupled with diffusive/active transport mechanisms within lignocellulosic materials
  - Imaging - methods to quantify pretreatment effectiveness
    - HSI, TEM, STM, AFM, XRD, LC-MS, GC-MS
  - Spectroscopic investigations as a function of pretreatment/processing conditions
    - FTIR, Raman, SERS, NMR

Cellulosic Biomass:

Big Potential, Complex Problems

- About half of the carbonaceous compounds in terrestrial biomass are cellulose, which is the most prominent single organic compound on earth.
- The net primary production of biomass was estimated to be 60 Gt/annum of carbon in terrestrial and 53 Gt/annum in marine ecosystems (1 Gt = 1012 kg) (Cox et al. 2000).
- Almost all of the biomass produced is mineralized again by enzymes which are provided by microorganisms.
- Cellulose is a chemically homogeneous linear polymer of up to 10 000 D-glucose molecules, which are connected by ß-1,4-bonds. As each glucose residue is tilted by 180° towards its neighbors, the structural subunit of cellulose is cellobiose
- The chemical uniformity provokes spontaneous crystallization of the cellulose molecules, the tightly packed microfibrils. Cellulose thus is a sturdy material ideally suited to insure the structural stability of land plants where it is a main component of the primary cell wall, especially in wood.
- Although crystalline cellulose is chemical homogeneous, no single enzyme is able to hydrolyze it, whereas soluble cellulose derivatives are easily degraded by a single endo-ß-1,4-glucanase.
- Enzyme mechanisms generally depend on single molecules fitting in their substrate pocket - with cellulose the substrate is much larger than the enzyme
- The crystalline material is hydrolyzed by a number of simultaneously present, interacting enzymes, or alternatively by a multienzyme complex found in anaerobic micro-organisms (cellulosome).
- Cooperation with non-catalytic specific binding modules (the carbohydrate binding proteins or modules) the enzymes are able to disrupt the crystal surface at the solid-liquid interphase, to make single cellulose fibers accessible for hydrolysis.
- The investigation of the hydrolysis mechanisms of cellulases opens up a new way of looking at enzymatic activity: the dualism between mechanical and structural "preparation" of the insoluble (crystalline) substrate followed by the hydrolytic activity on a released molecule (Sheehan and Himmel 1999).

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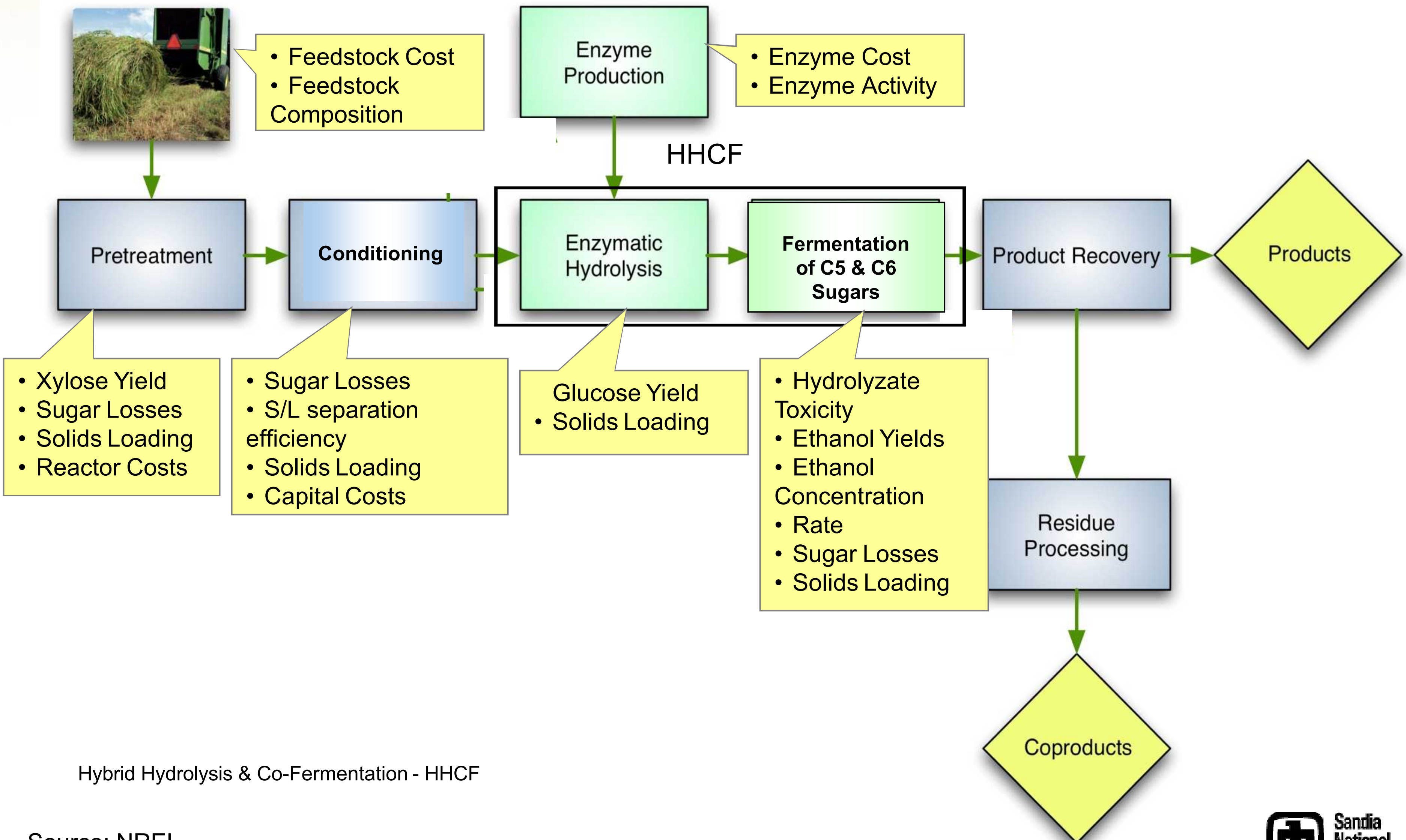
Role of Enzymes in Cellulosic Ethanol Production



Hybrid Hydrolysis & Co-Fermentation - HHCF

Source: NREL

Move Toward Greater Process Integration

Evolution of Biomass Processing Featuring Enzymatic Hydrolysis

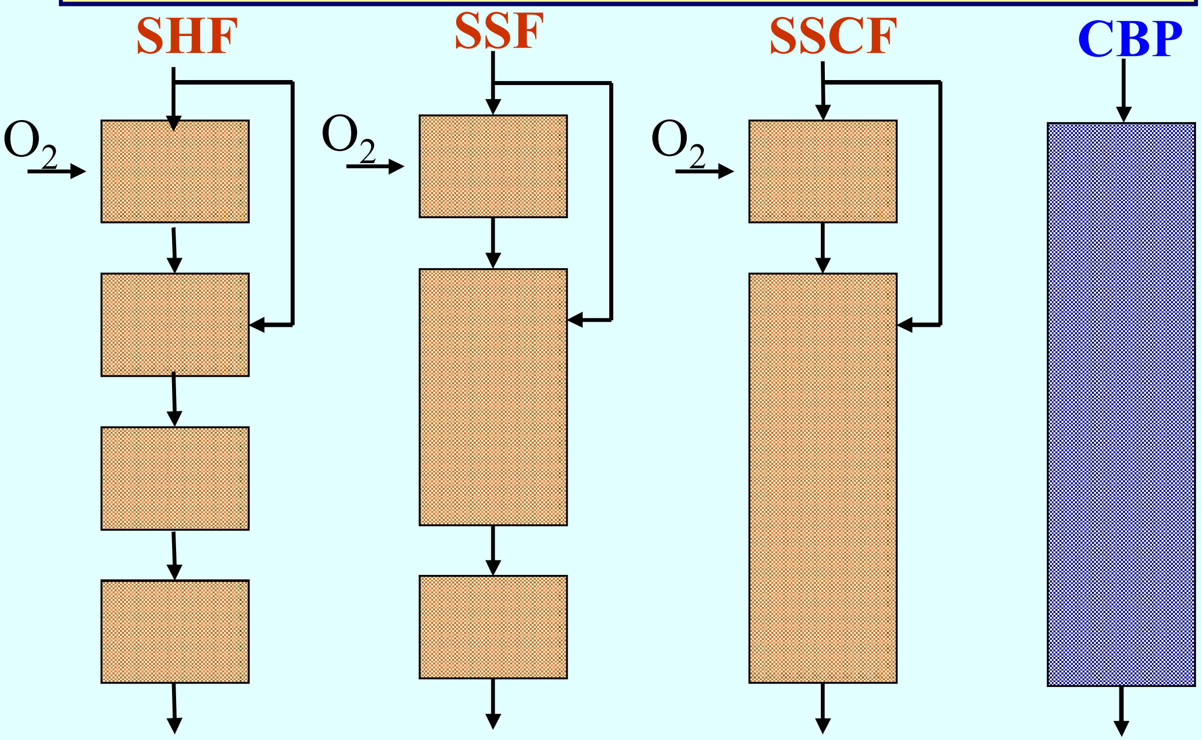
Biologically-Mediated Event	Processing Strategy (each box represents a bioreactor - not to scale)

Cellulase production

Cellulose hydrolysis

Hexose fermentation

Pentose fermentation



SHF: Separate hydrolysis & fermentation

SSF: Simultaneous saccharification & fermentation

SSCF: Simultaneous saccharification & co-fermentation

CBP: Consolidated bioprocessing

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Fundamental Mechanisms of Cellulase Hydrolysis

- Three basic cellulase enzymes: endoglucanase, exoglucanase, β-glucosidase
- Cellulases differ not only in the action mode (endo or exo), but also in the way they bind to the crystalline surface of the substrate.
- There are two sites in the enzymes which mediate binding: the active site of the catalytic domain and the separately folded and functionally independent carbohydrate binding module (CBM) which usually is attached through a PTS-box.
- The essential function of the CBM was shown for cellobiohydrolase CBHI from T. reesei, for which a detailed 3-dimensional model was constructed (Lee and Brown 1997).
- The catalytic domain without the CBM (the core enzyme) has a limited activity on cellulose.
- The deletion of CBMs has no effect for activity on soluble substrates (like CMC or barley ß-glucan) where the possible sites of activity on the substrate are not limited. (Tomme et al. 1995; Bolam et al. 1998).
- Members of each group have been investigated for their binding capacity for a number of polysaccharides: crystalline and amorphous cellulose, ß-1,3-glucan, xylan, starch, chitin and others (Tomme et al. 1998).
- Even within one family binding to different substrates is possible (Zverlov et al. 2001). Although CBMs bind to the cellulose with a high association constant and sometimes irreversibly, they show, in conjunction with a catalytic domain, surface diffusion and redistribute on the surface (Jervis et al. 1997; Carrard et al. 2000).
- Although CBMs are important for the processivity of cellulases (Irwin et al. 1998), there is no hint for a driving force, neither by the CBM nor by the catalytic unit.

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Ligninase

- **Lignases (a.k.a. ligninase)**
  - Goal: Develop more efficient conversion of lignin into hi-value products and/or alternative fuels through biochemical or chemical conversion technology. Develop model lignin system for study.
  - Currently a huge gap in understanding this system
  - Enzyme structure/function studies
    - Rational design/directed evolution
    - Mechanisms of lignin breakdown
    - Determine the mechanisms of lignin conversion, the role of enzyme binding
    - Catalytic and binding domains within lignin – new pretreatments?
    - Kinetic studies of lignin conversion
    - Alleviate product inhibition through chemical and structural modifications
  - Lignin studies
    - Fundamental science of lignin composition and structure
    - Imaging and
    - Modeling coupled with active transport

Overall Enzyme Research Goals

Fundamental R&D Opportunities:

- Develop advances in S&T that enable revolutionary progress in the efficient and cheap pretreatment and conversion of lignocellulosic materials into fermentable sugars
- Develop a fundamental understanding of enzyme-substrate and enzyme-enzyme complexes that play a role in biomass depolymerization and hydrolysis
- Development of new microsystem-based high-throughput screening technology for enhanced rational design of enzymes
- Utilization of BES funded world-class imaging and tools to generate new insight into mechanism of lignocellulose deconstruction and enzymatic hydrolysis
- Utilization of BES funded world-class biophysical characterization tools to generate new insight into enzyme kinetics and local environments of lignocellulose degradation
- Apply massive parallel computational modeling resource to understand enzymatic complexes and their role in biomass hydrolysis
- Synthetic -> biological -> synthetic

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Road Blocks

- Robust information on enzyme characteristics/crystal structures outside of enzymes derived from the dominant model system: *T. reesei*
- Efficient processing and annotation of vast genomics information directly applicable for the rational design of biomass-related enzymes
- Process compatibility – consolidated bioprocessing as a model system
- Accurate and robust kinetic assays (new molecules, new diagnostics) amenable to high-throughput screening techniques
- Lack of fundamental knowledge of lignocellulose as a composite material with unique and distinct binding sites and cross-linked structures as a function of feedstock
- Efficient pretreatment with minimal production of adverse co-products
- Lignin

Cellulosomes:

Bacterial Assemblages of Cellulolytic Enzymes

- **Cellulosomes are cell protuberances which tightly bind to crystalline cellulose (Lamed et al. 1987; Mayer et al. 1987). T**
- **They mediate a close neighborhood between cell and substrate and thus minimize diffusion losses of hydrolytic products, which is thought to be a major advantage for attached cells.**
- **A cellulosome preparation contains a number of different proteins, most of them having enzymatic activity. However, attempts for mild denaturation, purification of single components and reconstitution were only partially successful (Beattie et al. 1994; Bhat et al. 1994; Choi and Ljungdahl 1996).**
- **in all cellulosomes investigated so far the components of the multienzyme complex are strongly bound to each other by a duplicated, non-catalytic segment of 22 amino acid residues found to be conserved in all enzymes which are located in the cellulosome (Tokatlidis et al. 1991).**
- **This dockerin module binds specifically to the cohesin modules, located in a non-catalytic cellulosome component, for which the term "scaffoldin" was coined (cellulosome structure).**
- **The catalytic components themselves are complex proteins consisting of catalytic and non-catalytic modules. Binding of the cellulosome to the crystalline substrate is mainly mediated by a very strongly binding CBM IIIa module of the scaffoldin.**
- **The production of the multienzyme-complex "cellulosome" may have a number of advantages for the effective hydrolysis of cellulose:**
  - **synergism is optimized by the correct ratio between the components, which is determined by the composition of the complex;**
  - **non-productive adsorption is avoided by the optimal spacing of components working together in synergistic fashion;**
  - **competitiveness in binding to a limited number of binding sites is avoided by binding the whole complex to a single site through a strong binding domain with low specificity**
  - **stop of hydrolysis on depletion of one structural type of cellulose at the site of adsorption is avoided by the presence of other enzymes with different specificity.**

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R&D Opportunities: Cellulosome

- Role of location, structure, and complexation in overall efficiency
- Is there any process gain in the cellulosome vs. free bulk enzymes?
- Cellulosomes in extreme environments
  - Enhanced shielding and stability
- Make a synthetic scaffolding structure relevant to industrial processes
- Fundamental understanding of the cellulose-cellulosome interface

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JBEI Progress

Significant Milestones And Status

- JBEI successfully completed first DOE OBER review – 9/08
- JBEI commissioned by DOE Secretary Bodman – 12/08
- JBEI hosted visit and tour from Dr. Ray Orbach – 12/08
- Complete fist metabolic profiling of rain forest and compost community samples using mini-reactors (9/08)
- Complete characterization of one targeted feedstock under ionic liquid pretreatment conditions (7/08)
- Complete first generation cellulase engineering activity (9/08)
- Automated parallel PCR reactions for 96 samples performed in 1 day using high-throughput expression factory (9/08)

Other Activities

- JBEI has hosted several VIPs and congressional staffers
- JBEI was highlighted during LBNL Board of Directors Review
- JBEI featured in WSJ, NY Times, Discover, Newsweek, and SF Chronicle
- FY09 milestones are on-schedule to be completed as per original project plan

jbei
Joint BioEnergy Institute

Sandia National Laboratories

DARPA Biofuel Program
Sandia on UOP Team funded under BAA06-43*

Opportunity

Current program is a "*build-down*" process using long C chain feedstock

Broad feedstock mixture

"Build-down" process:
cracking/isomerization of C12-C16
+ additives

JP-8 surrogate

Potential Users
- U.S. military JP-8 platforms
- Commercial aviation

- Develop a process to JP-8 that is affordable and feedstock-adaptable
- Demonstrate 60% energy conversion process to JP-8; analyze opportunities to 90%
- Deliver 100L sample for government testing and evaluation
- Develop a commercialization plan for cheap and readily available fuel
- Develop a qualification plan for DoD acceptance of JP-8 surrogate
- Develop economic production cost models

Technologies now exist

New program will focus on a cellulosic "*build-up*" process and algae oil affordability

Technical area 1: cellulosic materials to JP-8
Develop highly-efficient conversion process to JP-8 from short chain cellulosic materials

Technical area 2: algal to JP-8
Develop highly-efficient system for low-cost algal oil production and optimize conversion to JP-8

"A" Approved for Public Release – Distribution Unlimited

*** Project completed 1Q-FY09**

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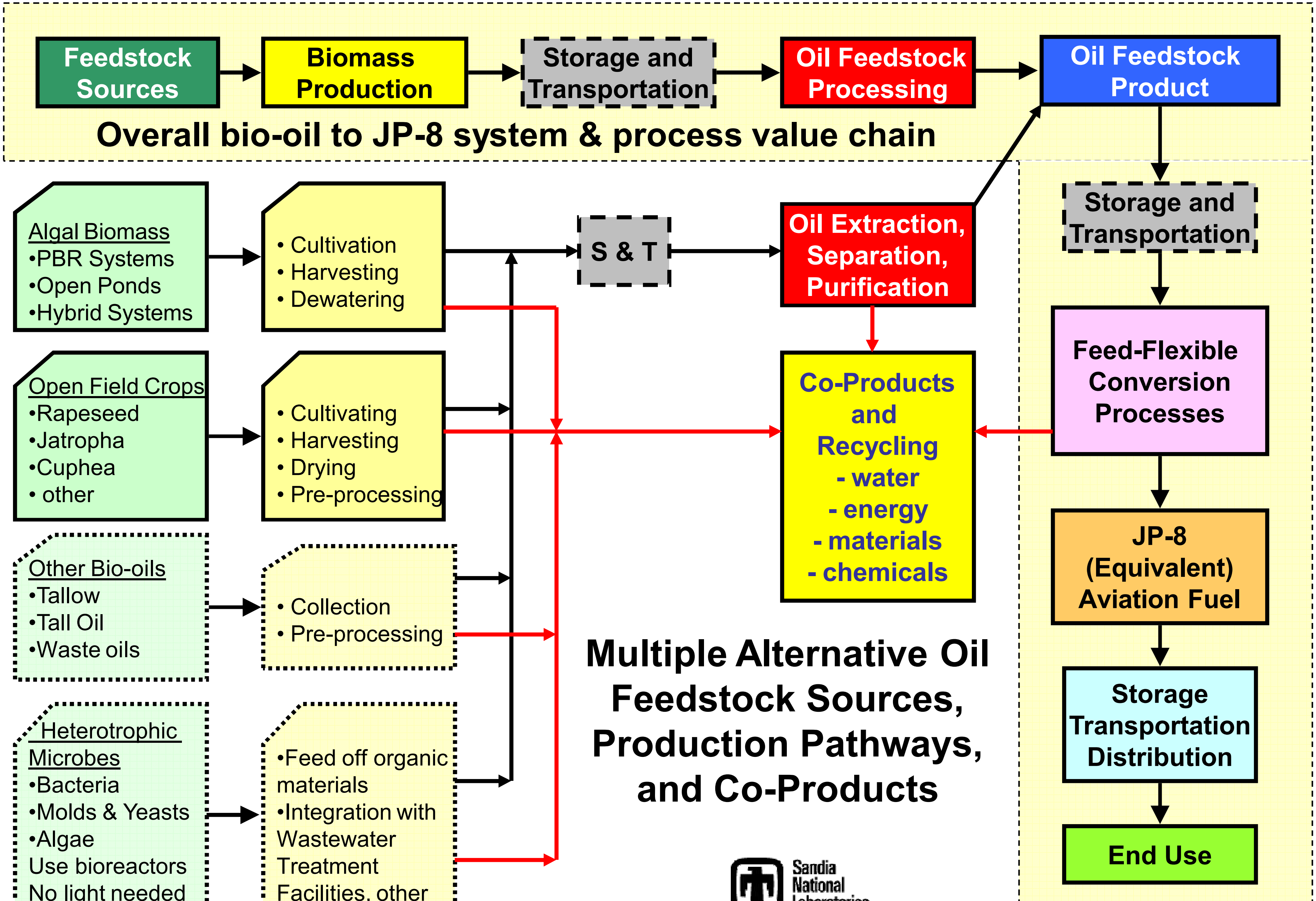
Sandia Role: *Feasibility Analyses for Bio-Oil-to-JP8 Scale-Up*



Initial Look at Oil Feedstock Production Scale-up Potential with Wheat-Rapeseed Rotation

- Use of cropping information from USDA / WSU
- Avoid competition with corn and soy acreage, but otherwise keep analysis relatively "unconstrained"
- Identify acreage and production potential
- Estimate break-even cost of production
- Extend to other target oil crops and cropping options
- Apply additional constraints as analysis progresses

BioFuel Variety Trials

Harold P. Collins, Rick Boydston, and Ashok Alva, USDA-ARS, Prosser, WA
An Hang, Steve Fransen and Phil Wanderschnieder, Washington State University, Prosser, WA

OILSEED CROPS

Cruciferae family

RAPESEED AND CANOLA *Brassica napus or B. campestris*

	Range: Erucic acid % in oil	Range: Glucosinolate µmole in g oilfree meal
RAPESEED	2 to 55	>30
	<2	>30
	>2	<30
CANOLA	<2	<30

	Spring Type	Winter Type
Planting date	Mid Apr - Mid May	Late Aug - Mid Sep
Bloom	30 to 45 dap†	Mid to Late Apr
Harvest	110 - 120 dap	300 - 310 dap
Yield (lbs/a)	2000 - 2500	4000 - 4500
Oil content	40-45 %	40 - 45 %

Cruciferae family

MUSTARD AND CRAMBE (*Sinapsis alba/Crambe abyssinicia*)

	Range: Erucic acid % in oil	Range: Glucosinolate µmole in g oilfree meal
MUSTARD	>2	>30
CRAMBE	40 to 50	>30

	Range: Yield Lbs/ac	Range: Oil Content %
MUSTARD	1500 - 1800	25 - 27
CRAMBE	1500 - 2000	28 - 30

Both crops are planted in the spring and required 110 to 120 dap to mature.

Compositae

SAFFLOWER (*Carthamus tinctorius*)

Planted:	Early Spring
Growing season:	150 - 160 dap
Yield:	3500 - 4000 lb/a (85 - 100 bu/a)
Oil content:	42 - 48 %

Leguminosae

SOYBEAN (*Glycine max*)

Planted:	Late Spring (to avoid frost damage/kill)
Growing season:	140 to150 dap
Yield:	3000 - 3500 lbs/a (50 to 60 bu/a)
Oil content:	20 - 22 %

†dap: days after planting.

Plant	Yield (seed) lbs/acre	Biodiesel gal/ acre	Plant	Yield (seed) lbs/acre	Biodiesel gal/ acre
Corn	7800	18	Safflower	1500	83
Oats	3600	23	Rice	6600	88
Cotton	1000	35	Sunflower	1200	100
Soybean	2000	48	Peanut	2800	113
Mustard	1400	61	Rapeseed	2000	127
Camelina	1500	62	Coconut**	3600	287
Crambe	1000	65	Oil palm**	6251	635

** Yield given in lbs of oil /acre.

OBJECTIVE: To quantify the environmental and economic benefits of incorporating a sustainable oil-seed biofuel crops in irrigated vegetable rotations.

To determine:
1) the energy balance (input-output balance for petrochemicals vs biodiesel yield;
2) the C balance, trace gas emissions (N_20, CH_4 and CO_2) and nutrient budgets and;
3) production sustainability and profitability.

Rapeseed

Safflower

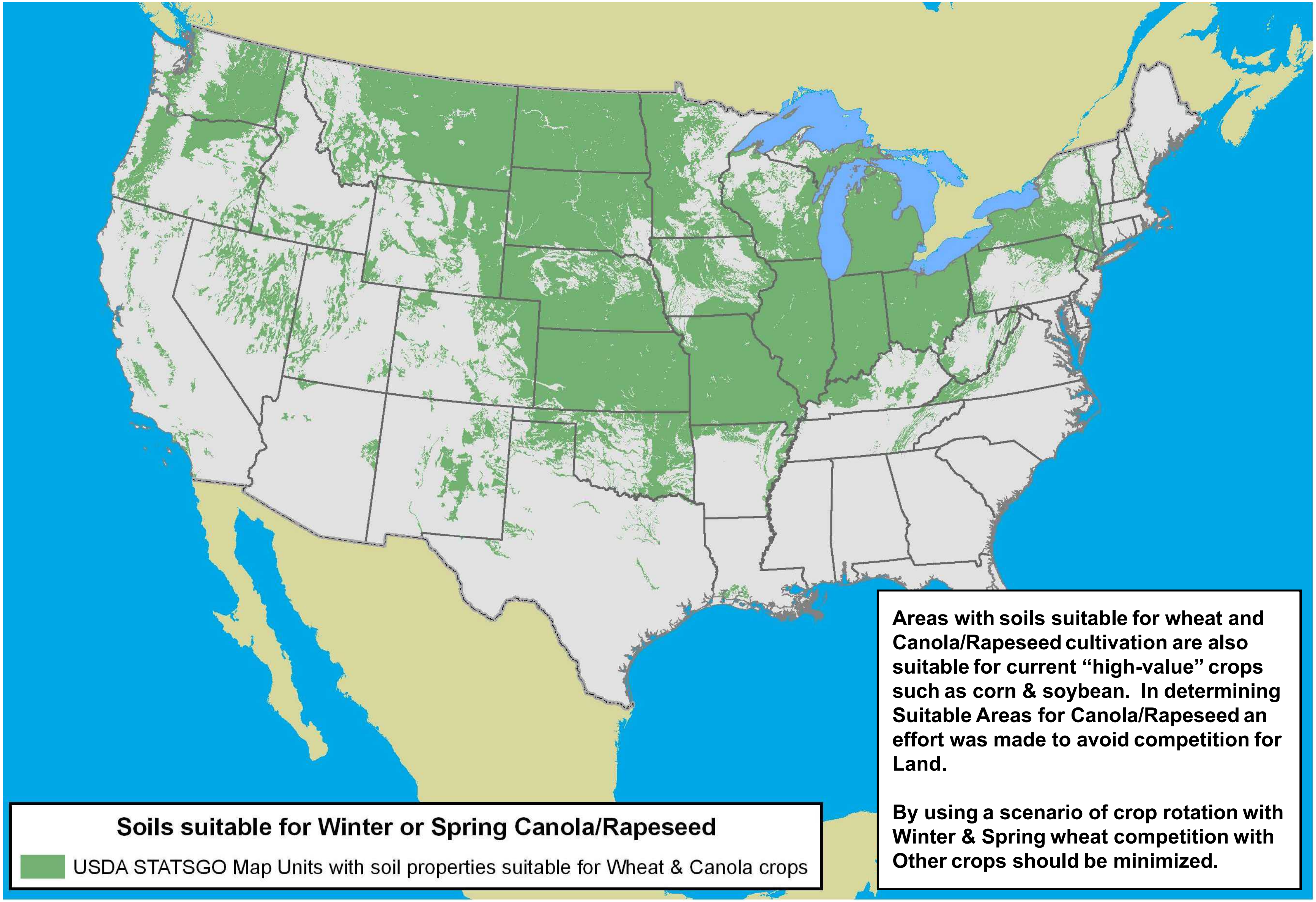
Crambe

Mustard

Sunflowers

Soybean

Assessment of Potential Oil Feedstock Scale-Up by Crop Rotation of Rapeseed with Wheat while avoiding Competition w/ Corn & Soy



Areas with soils suitable for wheat and Canola/Rapeseed cultivation are also suitable for current "high-value" crops such as corn & soybean. In determining Suitable Areas for Canola/Rapeseed an effort was made to avoid competition for Land.

By using a scenario of crop rotation with Winter & Spring wheat competition with Other crops should be minimized.

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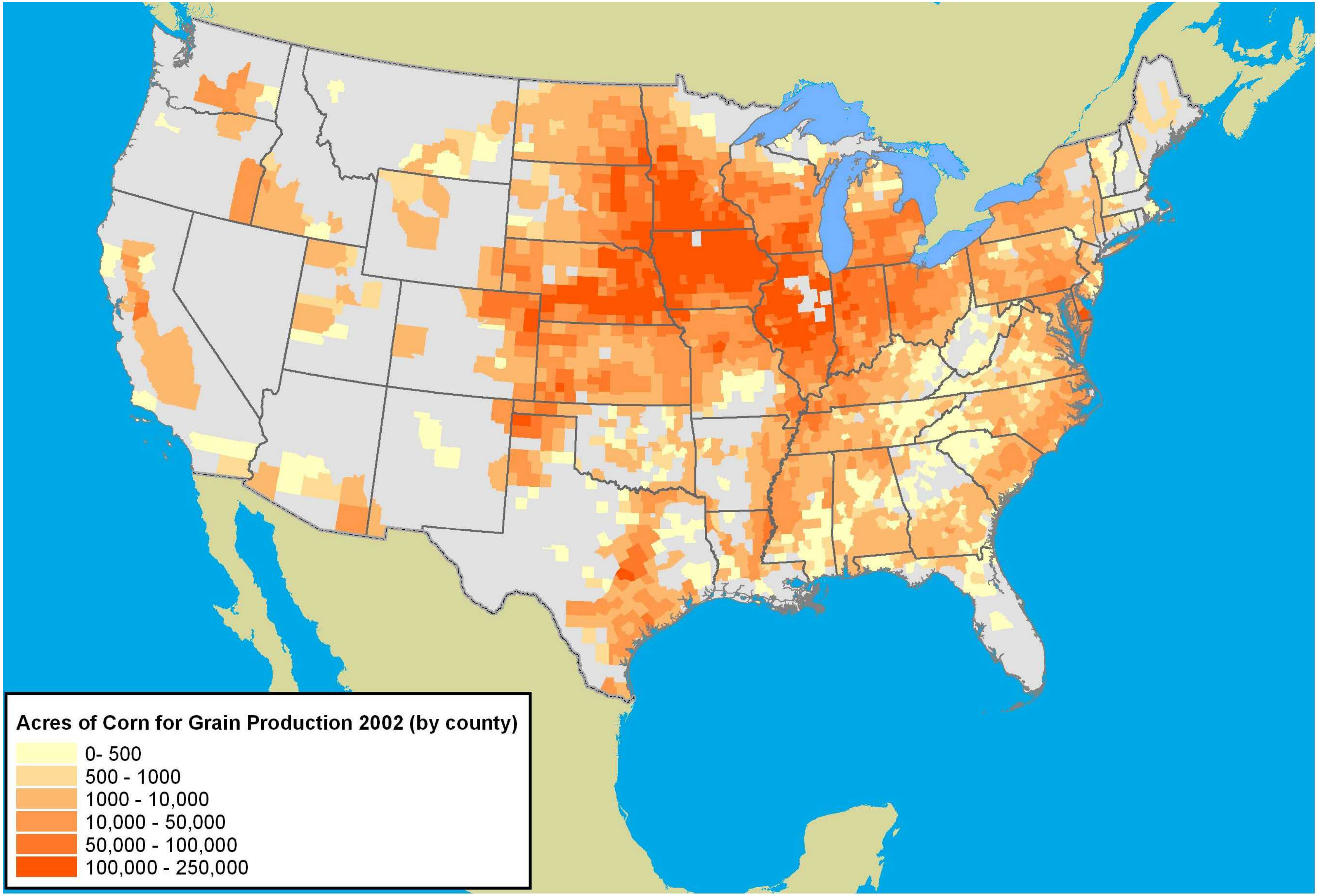
Assessment of Potential Oil Feedstock Scale-Up by Crop Rotation of Rapeseed with Wheat while avoiding Competition w/ Corn & Soy



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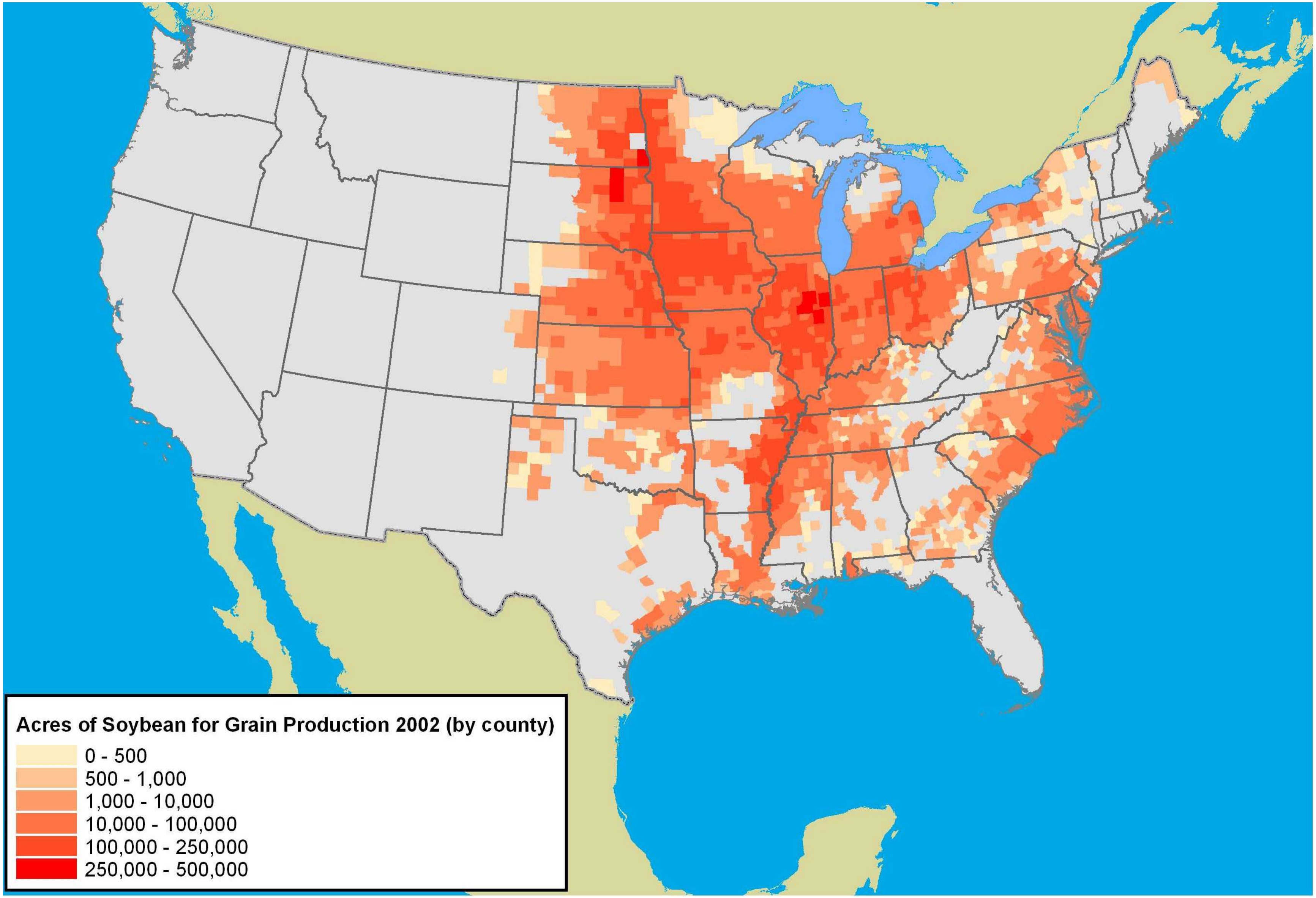

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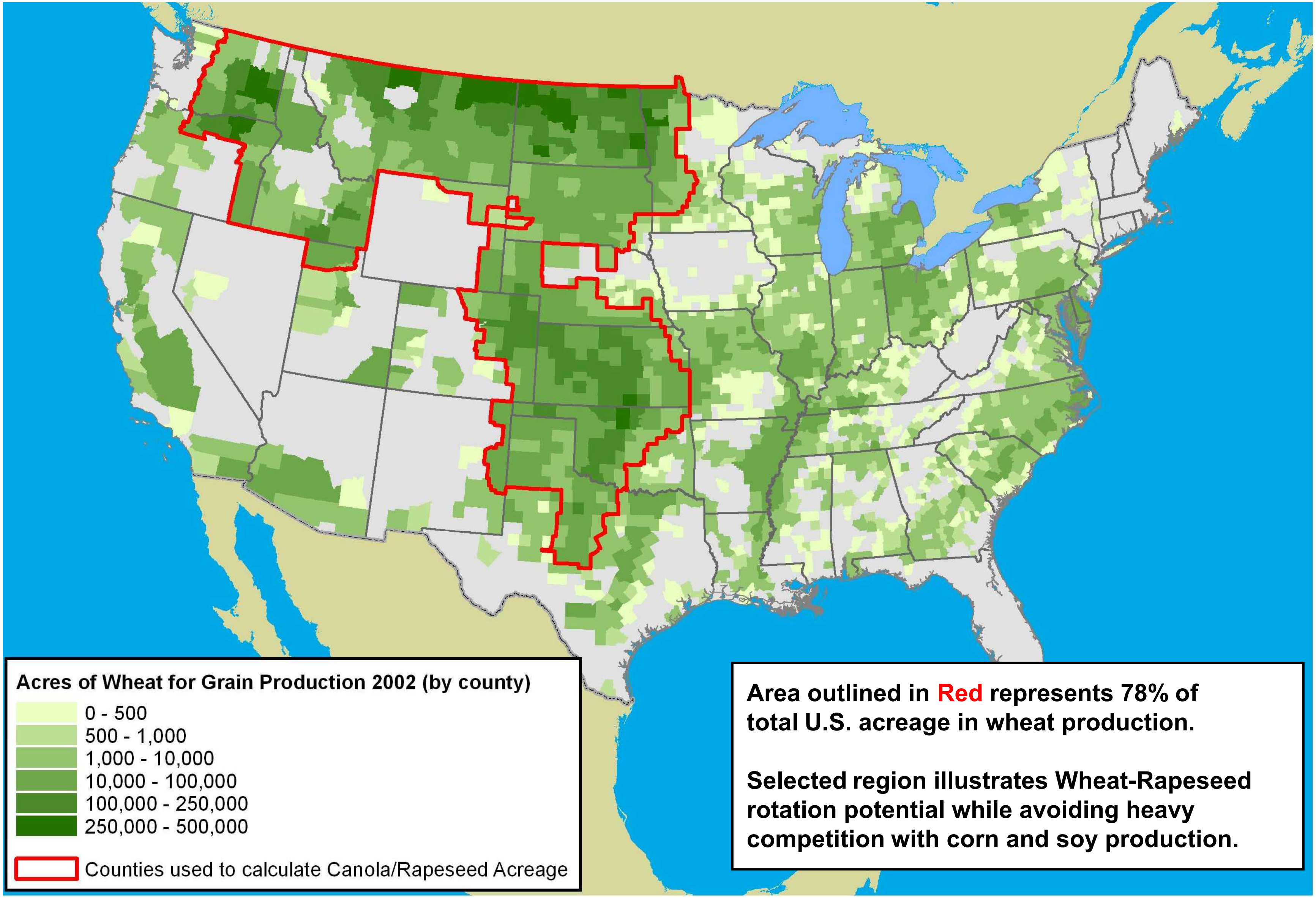

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Wheat-Rapeseed Rotation Potential

Total U.S. Acres in Wheat	47,524,791	acres
Wheat Region acreage (see map) [78% of total acres of wheat production]	37,444,009	acres
Annual Available Acres with Crop Rotation of W/R/W (Wheat-Rapeseed-Wheat)	18,722,005	acres
Annual Available Acres with Crop Rotation of W/R/F (Wheat-Rapeseed-Fallow)	12,481,336	acres
Average yield per acre (lbs)	2,750	pounds
Minimum Yield per acre (lbs) [non-irrigated]	1000	pounds
Maximum yield per acre (lbs) [irrigated]	4500	pounds
Average Annual yield (lbs) [W/R/W]	51,485,512,375.00	pounds
Minimum Annual yield (lbs) [W/R/W]	18,722,004,500.00	pounds
Maximum Annual yield (lbs) [W/R/W]	84,249,020,250.00	pounds
Average Annual yield (lbs) [W/R/F]	34,323,674,916.67	pounds
Minimum Annual yield (lbs) [W/R/F]	12,481,336,333.33	pounds
Maximum Annual yield (lbs) [W/R/F]	56,166,013,500.00	pounds
Average oil yield per acre (gal) (40% oil content & 7.8lbs per gal) [W/R/W]	2,640,282,686	gallons
Minimum oil yield per acre (gal) (40% oil content & 7.8lbs per gal) [W/R/W]	960,102,795	gallons
Maximum oil yield per acre (gal) (40% oil content & 7.8lbs per gal) [W/R/W]	4,320,462,577	gallons
Average oil yield per acre (gal) (40% oil content & 7.8lbs per gal) [W/R/F]	1,760,188,457	gallons
Minimum oil yield per acre (gal) (40% oil content & 7.8lbs per gal) [W/R/F]	640,068,530	gallons
Maximum oil yield per acre (gal) (40% oil content & 7.8lbs per gal) [W/R/F]	2,880,308,385	Gallons

* Note: With average yields and average operating costs, the break-even cost to produce oil from rapeseed is projected to be ~ $2 per gallon

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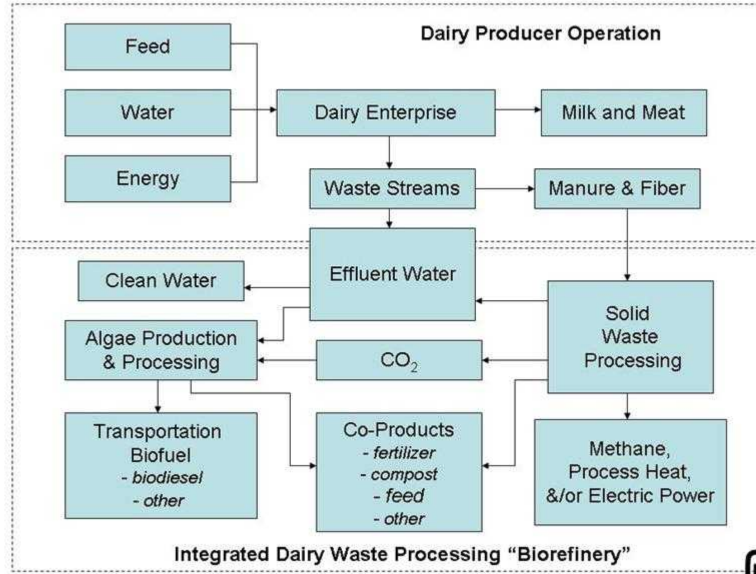
Sandia Support* to New Mexico Dairy Industry for Dairy Waste-to-Energy Project Development:

- **Manure to Methane or CHP**
- **Effluent to Algal Biofuels**

** Partnered also with NMSU and UNM*

NM-TRC Dairy Waste-to-Energy Project System Flows w/ Algal Biofuel Element



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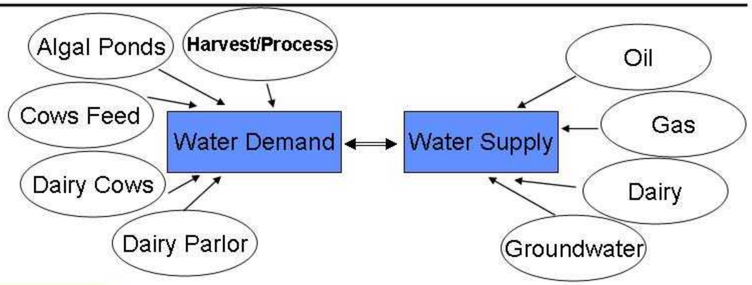
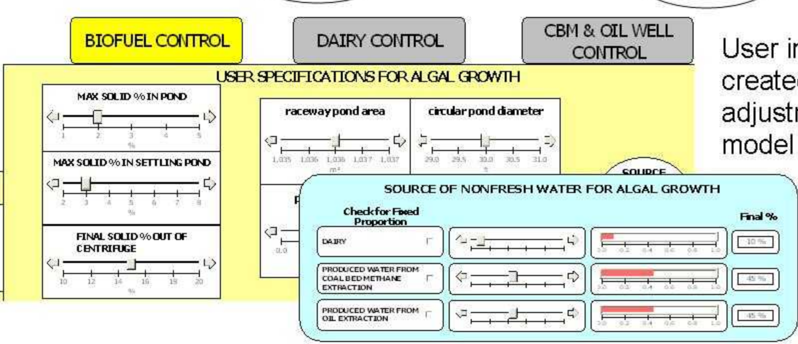
Water Balance in Biofuel Production and Water Reuse





User interface is created for adjustment of model parameters.

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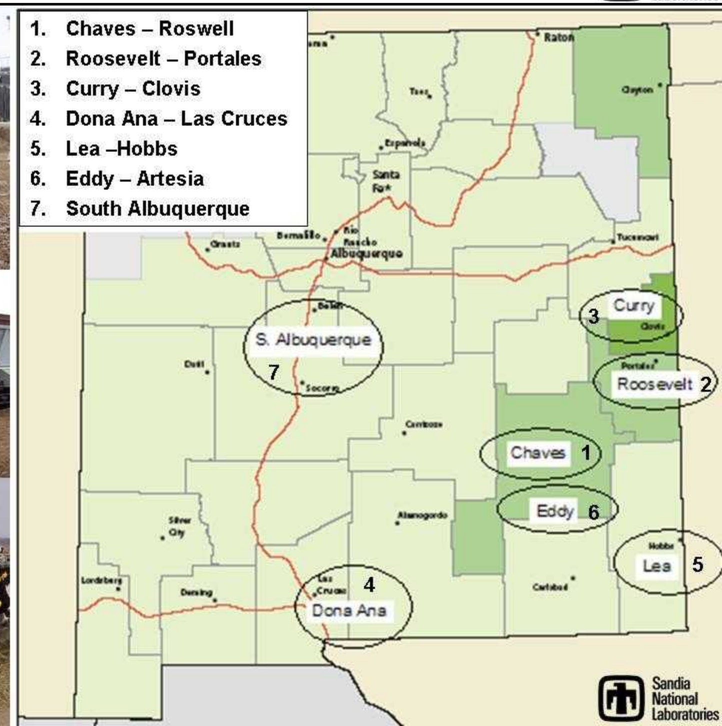

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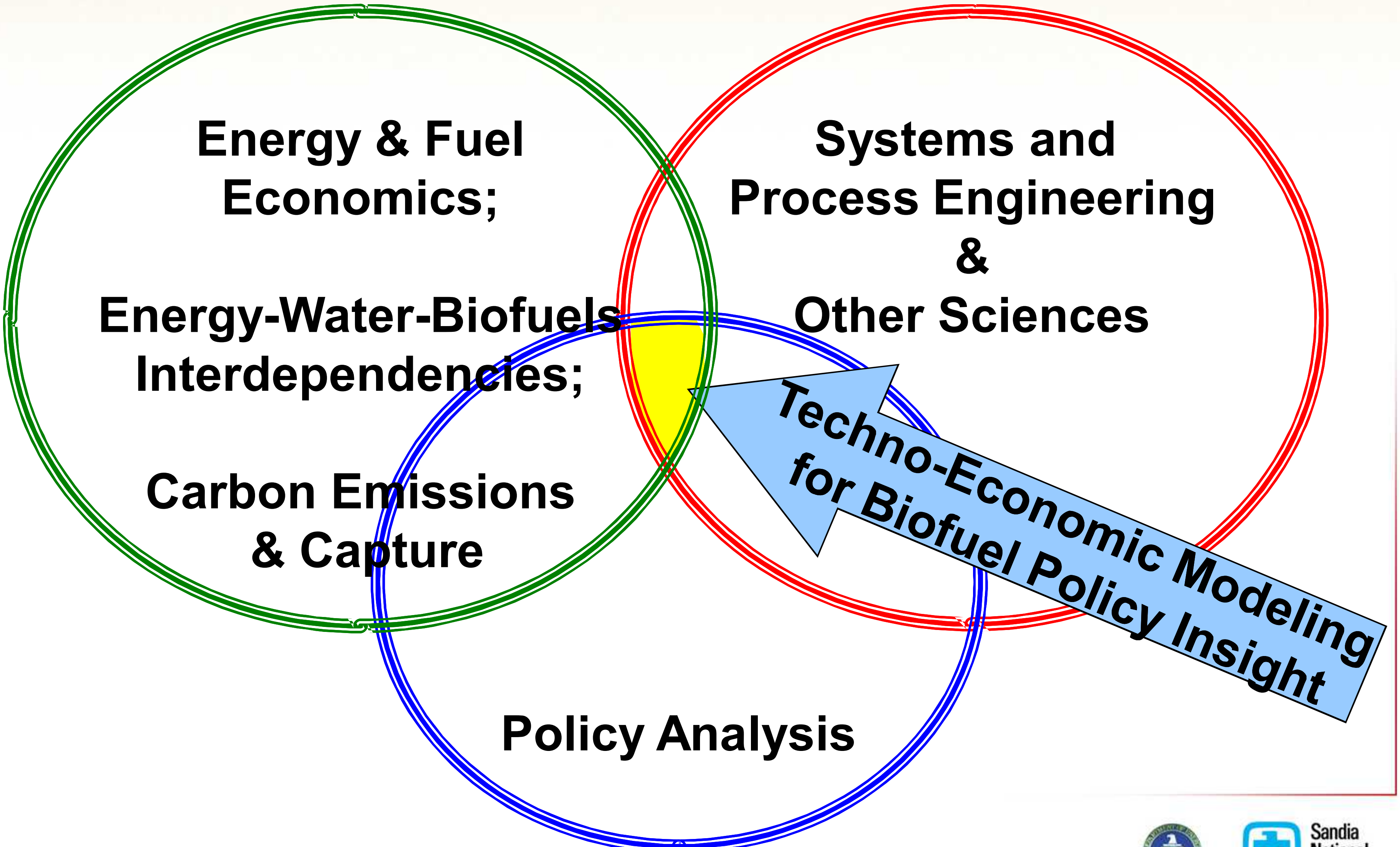
Techno-Economic Modeling & Analysis

Science & Technology-based Policy Insight



Techno-Economic Modeling & Analysis

To Inform Technical and Policy Decisions

- Assess technical performance & cost/benefit tradeoffs among different biofuel technologies, systems, and processes
- Assess economic impact of R&D strategies & investments
- Assess environmental impact of R&D strategies & investments
- Assess consequences & constraints of alternative pathways for feedstock, biofuels, & coproducts industry build-up
- Inform R&D and business development investment decisions
- Inform policy decisions … explore "what if " scenarios

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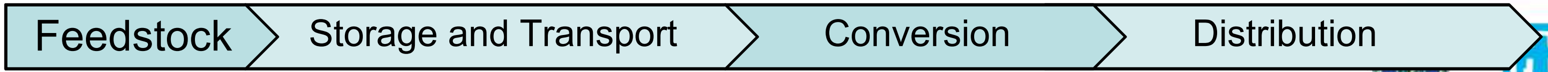
Biofuels Supply Chain Study

System Dynamics Modeling of Cellulosic and Starch Ethanol Biofuels

National Biofuels Deployment Model (BDM)

- Joint project done through CRADA with General Motors… completed Dec 2008.
- Assess the feasibility of achieving sustainable production of biomass feedstock and biofuel production capacity to displace 60 billion gallons of gasoline-equivalent fuel per year (90 billion gallons ethanol) by the year 2030.
- A comprehensive assessment of the <u>implications</u>, <u>limitations</u>, and <u>enablers</u> for realizing a significant production volume of biofuels for transportation.
- Identify and understand the interdependencies that exist between various segments of the biofuels lifecycle to identify significant obstacles and unique opportunities



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Sandia Research Specific to 3rd-Generation Algal Biofuel

- **Visible-IR and Lidar Remote Sensing** for broad area interrogation of algae pond productivity and health.
- **In-Situ Spectroscopic Monitoring w/ CFD Modeling** for ground-truthing and pond characterization.
- **Applied Biology** and metabolic pathways for GMOs, nutrient and CO_2 use, and laboratory to pond scale-up.
- **Harvesting, De-watering, and Extraction** technologies.
- **Techno-Economic Modeling** to inform technical and policy decisions.

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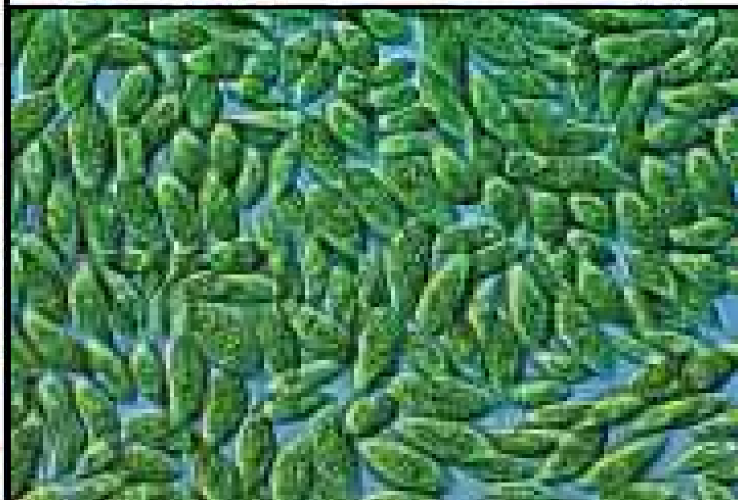
The Concept of Algae-Based Production of Biofuels, Co-products & Co-Services

Impaired Water
- brackish groundwater
- produced water
- desalination concentrate
- Ag wastewater
- Industrial wastewater
- Municipal wastewater
- Geothermal water & heat

Waste CO_2 & Heat
- Electric power generation
- Ag processing
- Industrial processing
- Wastewater treatment
- Desalination

Algae Production Systems
Ponds, PBRs*, Hybrid Systems†



Sunlight (photoautotrophic)

Organic Carbon (heterotrophic)

O_2

Biofixation of CO_2

Biomass Harvesting

Processing

Co-Products
- feeds
- fertillizers
- biopolymers
- glycerine
- other

Reclaimed Water
- nutrient removal

Biofuels
- biodiesel
- biogas
- ethanol
- JP-8

* PBRs = PhotoBioReactors

† Hybrid Systems = Ponds + PBRs

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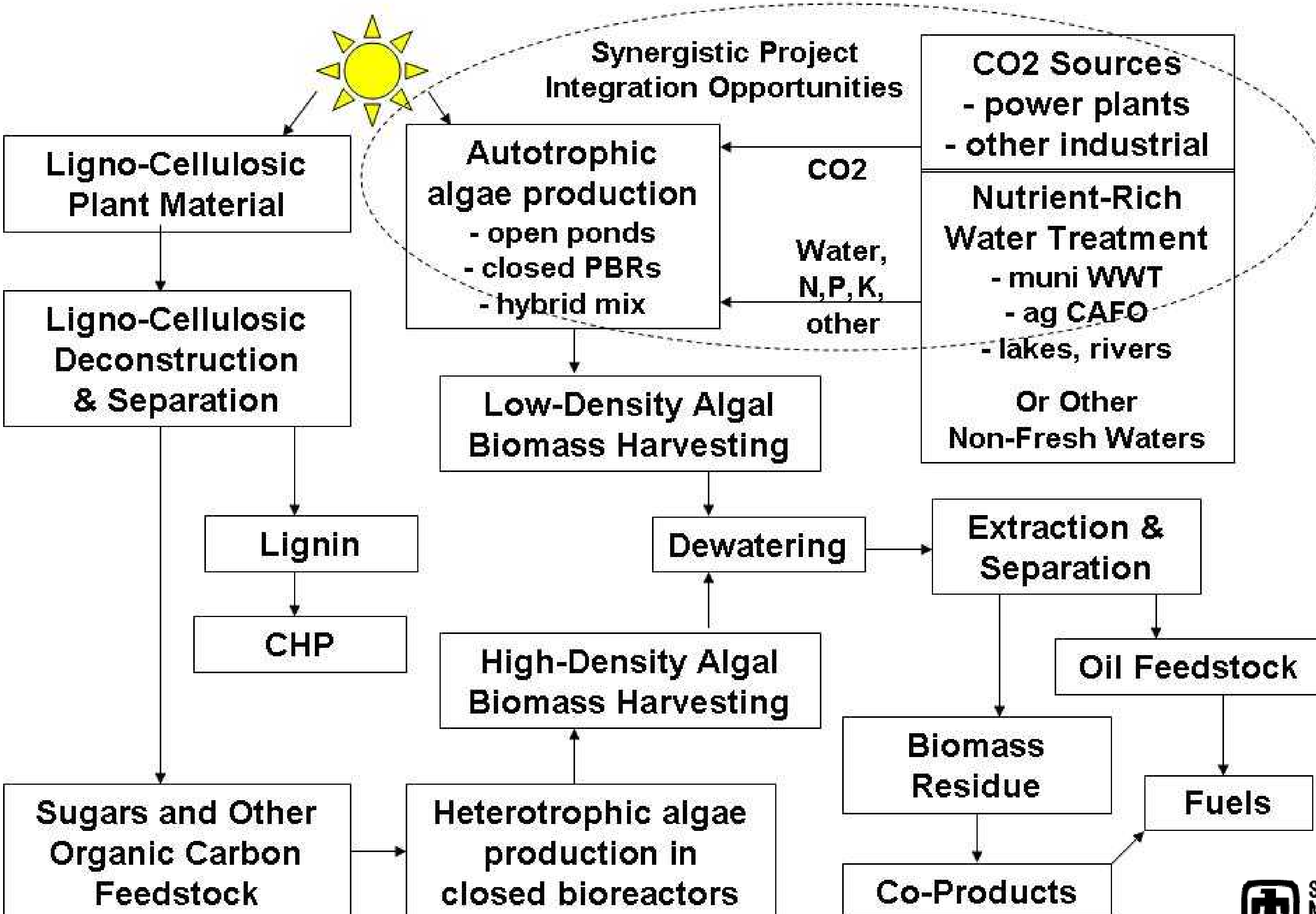
Major Paths for Algal Biofuels

Originating with Photosynthesis



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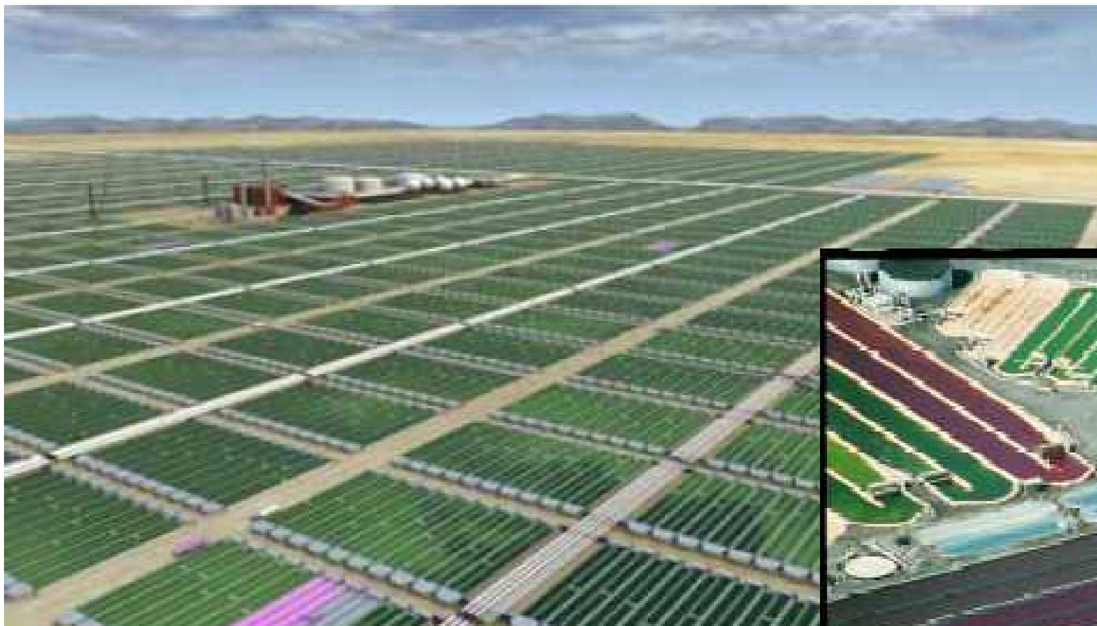
Algal Biomass Production Scale-up

Closed Photobioreactor (PBR) vs. Open Pond Systems

… Increased control & performance vs higher infrastructure costs ?
… Viability of scale-up for sustainable algal-based biofuel production ?
… Fewer large-scale centralized vs. many smaller-scale distributed facilities ?



Conceptual Ilustration of Commercial Scale Algal Biomass Production Facility using Closed Photobioreactor systems - Solix

Commercial Microalgae Production Facility using Open Raceway Pond Systems - Cyanotech Corporation, Kona, Hawaii

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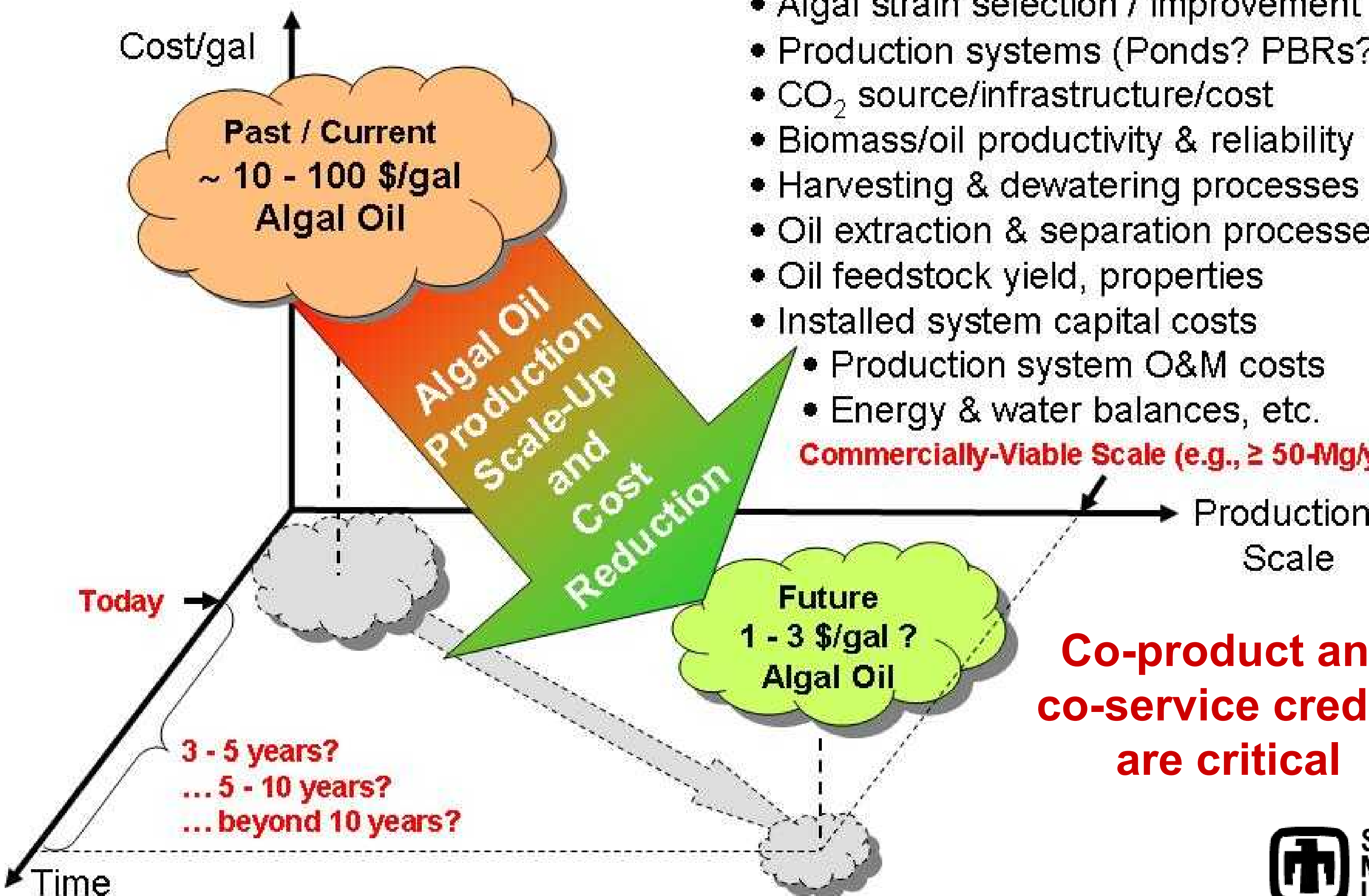
The Challenge for Algae-Based Biofuels

Reducing Algal Oil Production Costs

Systems and Processes Scale-up Issues/Challenges

- 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 are critical

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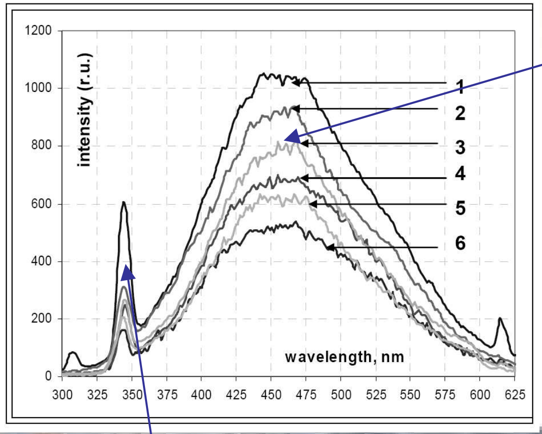
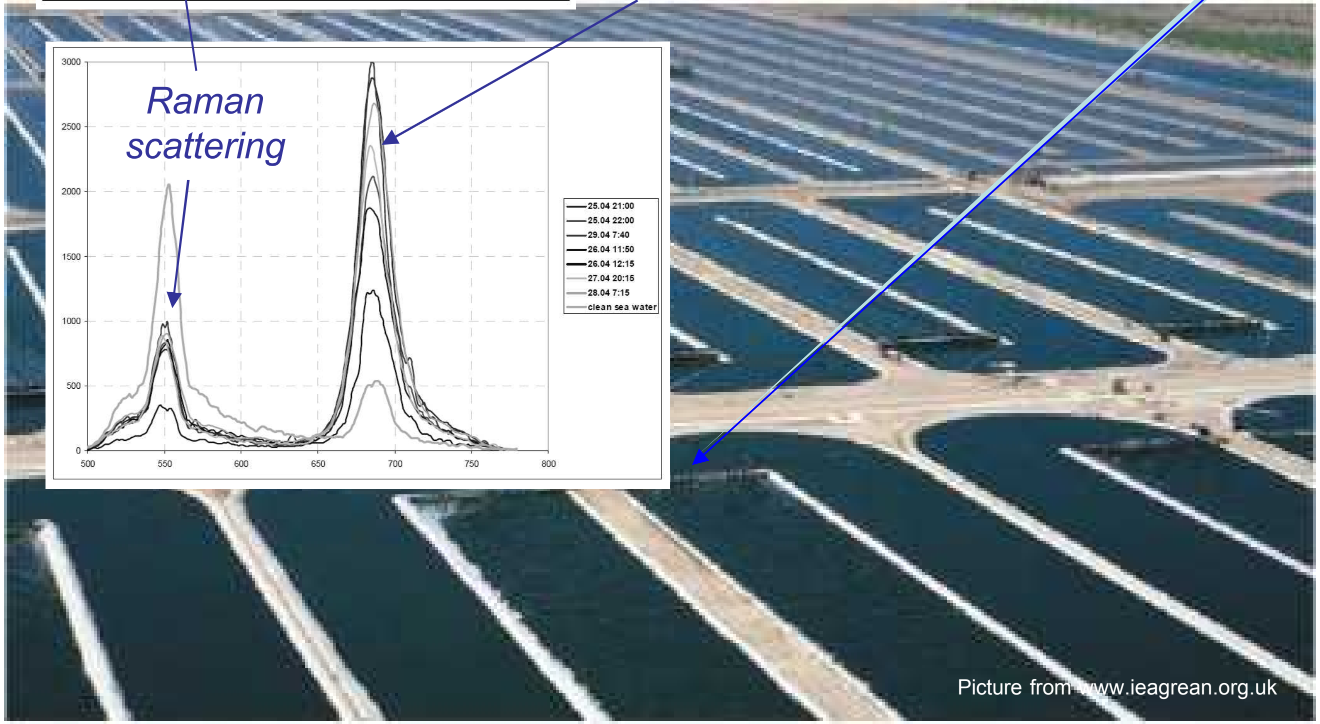
Improving Productivity of Algal Cultivation

Productivity & Health Characterization w/ Lidar & in-situ spectroscopic monitoring

Concept being pursued via LDRD

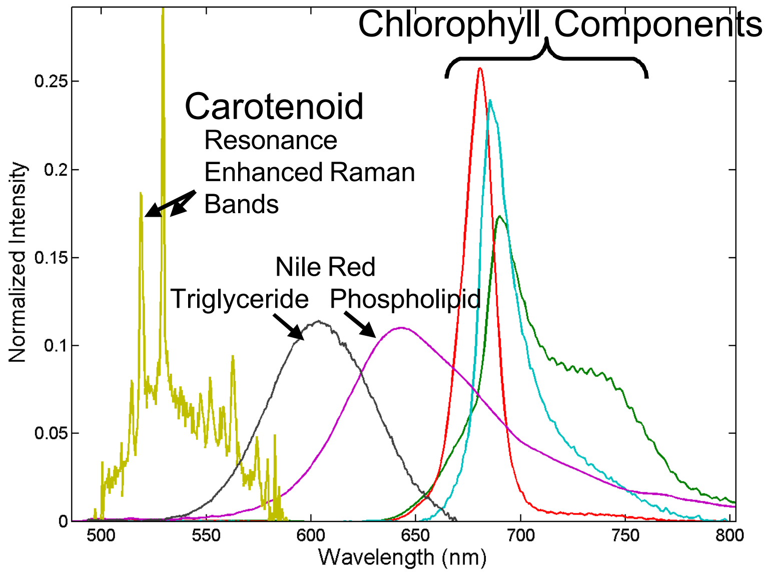
Spectral data from G. Pavelescu et al., "Water analysis from LIDAR investigations on the Romanian Black Sea coast," Proc. of SPIE **6743**, 67430P (2007).





In-Situ Spectroscopy Monitoring
Allows Non-invasive Characterization of Algal Cultivation Systems

- Fluorescence, Raman, and Near-IR monitor algal health, lipid production, nutrient concentration, dissolved gases, and physical characteristics (light, temperature, salinity).



In this case, label-free in-situ fluorescence of live algal cultures is being used to measure carotenoids as surrogates for spatial and quantitative monitoring of lipid production.

- In combination with remote sensing and CFD modeling, a rapid, complete, and continuous characterization of an algal pond is available.

CFD Model of Algal Raceway Pond

Modified EPA and US Army Corp of Engineering Codes

- The Environmental Fluid Dynamics Code (EFDC) solves 3D Navier-Stokes equations of open channel flow to model speed, temperature, and nutrient gradients.
- Solar insolation and other environmental forcing functions
- Includes algal biomass growth model
- CE-QUAL couples nutrient kinetics and 22 independent variables (N, P, Si, O_2…) to model growth rates.

$$\frac{\partial}{\partial t} B(\mathbf{x},t) = \left(P - B_M - P_R - W_S \frac{\partial}{\partial z} \right) B(\mathbf{x},t)$$

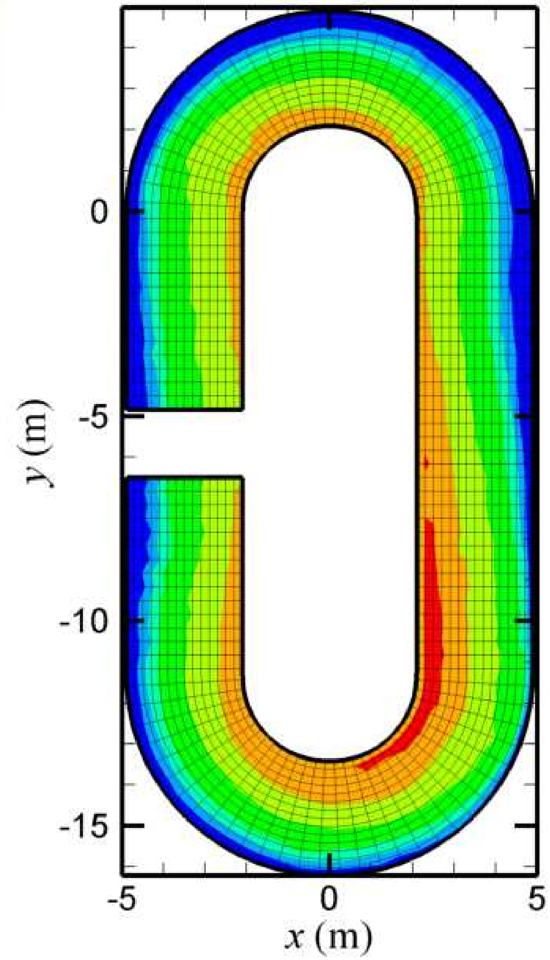
B(x,*t*) is the spatio-temporal algal biomass (gm Carbon/m^3)

P is the production rate (1/day)

BM is the basal metabolism rate (1/day)

PR is the predation rate (1/day)

WS is the settling velocity (m/day)



CFD Modeling with Remote Sensing and In-situ Spectroscopic Data

Provide Continuous On-line Pond Characterization and Systems Optimization

- Optimize system parameters to improve efficiency (raceway designs, nutrient loads, temperatures, etc.).
- Impact of various climates on growth rates and biomass productivity.
- Evaluate the impacts of various system parameters without having to risk an algal colony.
- Determine the feasibility and potential benefits of scaling up.
- Quantify the benefits of integrating algae culture ponds with waste treatment plants and fossil-fuel-based power plants.

Lab and Small Outdoor Scale Algae Cultivation Reactors

For Scale-up, Monitoring, and Systems Testing

Chlorella pyrenoidosa cultured in a 4L chemostat at SNL/NM.

Six-foot diameter algae growth tank with Air/CO_2 blower assembly in outdoor greenhouse facility at SNL/NM.

Not shown are other lab facilities growing algae for R&D at SNL/CA

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Harvesting, Dewatering, and Drying

Underappreciated energy-intensive process steps

Techniques that could avoid these steps would provide a major energy advantage

Algal Biomass Growth & Cultivation System → **Harvesting/ Separation** → **Dewatering** → **Drying** → **Oil Extraction & Separation** → **Neutral Lipid (oil) for biofuel feedstock**

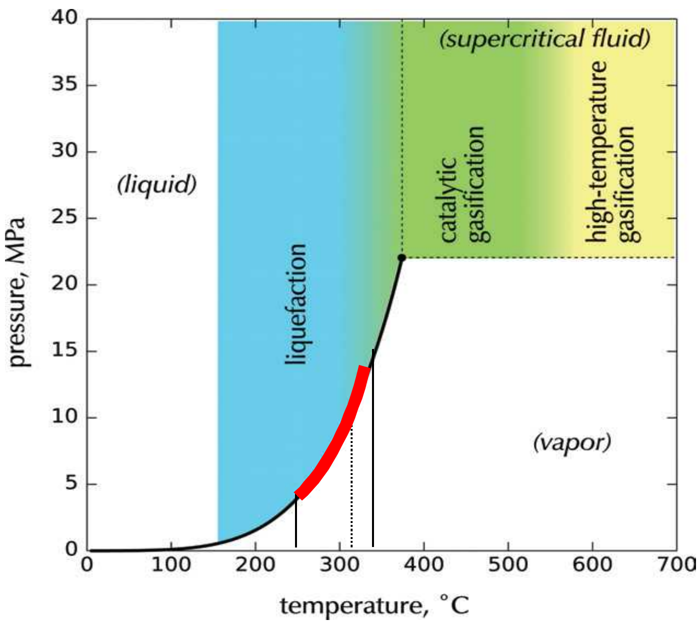
1-10% solids to 100% solids

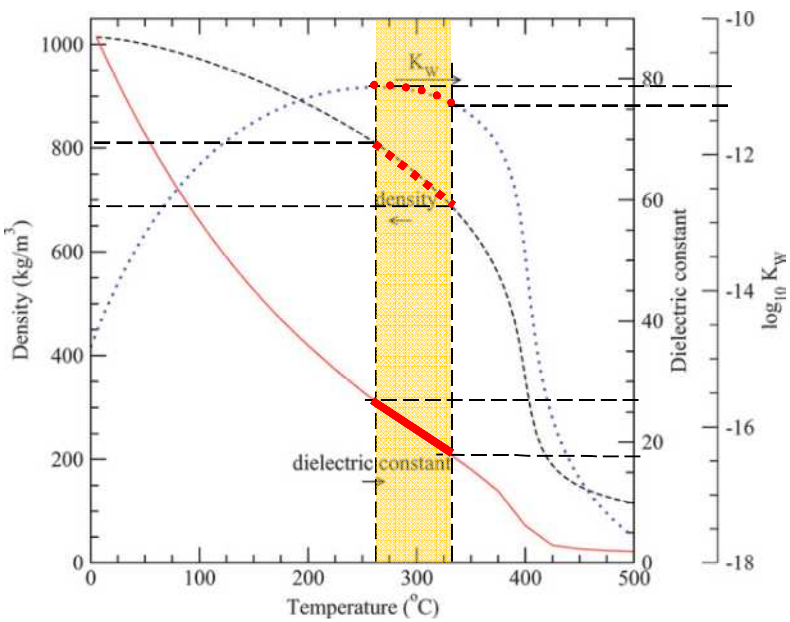
2.3 MJ/kg enthalpy of vaporization for water
≈40 MJ/kg enthalpy of combustion for biodiesel

1) **Small particle size (3-30 μm)**
2) **Low concentration of algae in water (typically ~1-gram of dry weight biomass per liter)**
3) **Negative charge on algal cells**

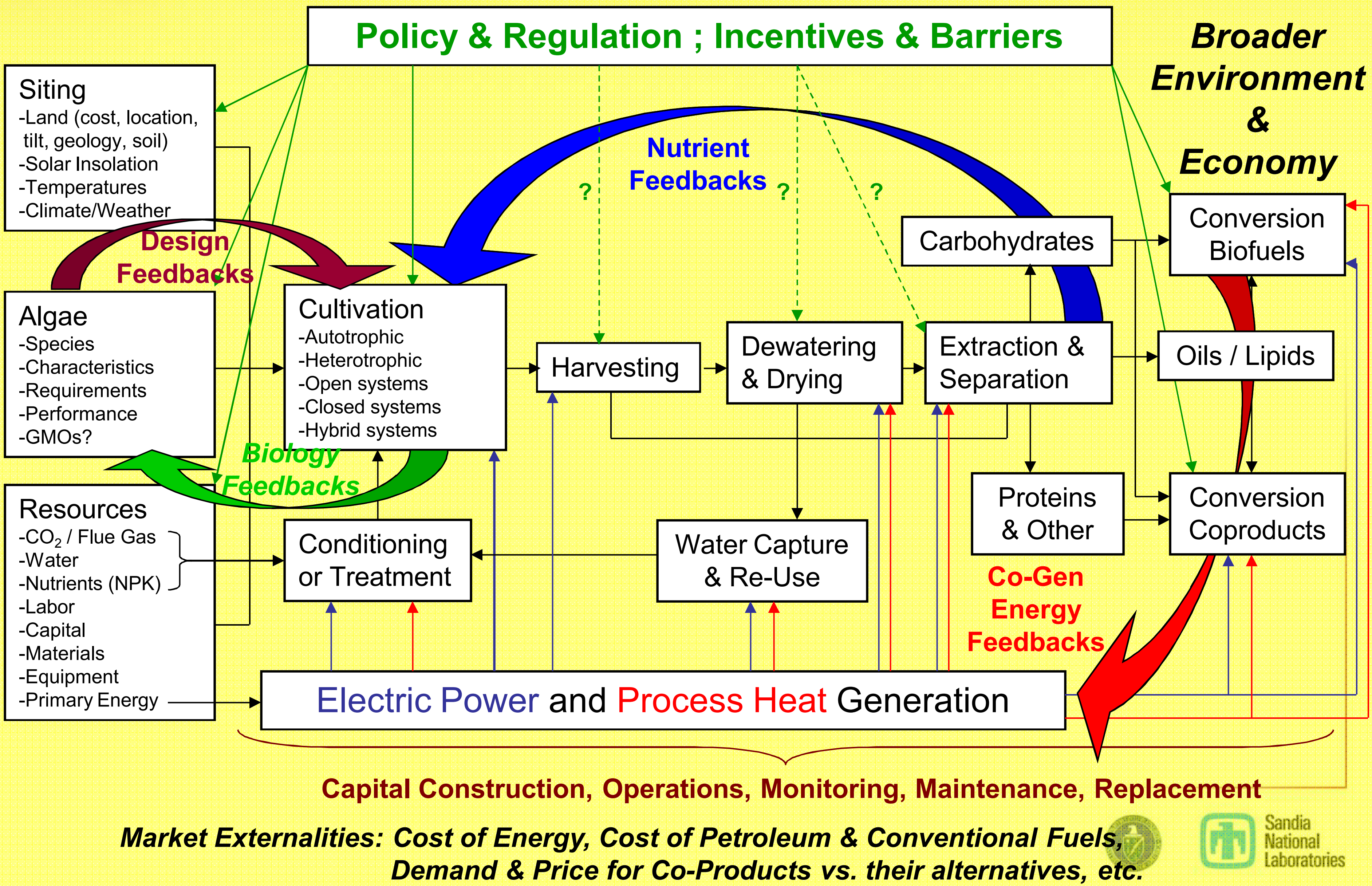
Supercritical MeOH and Subcritical Water Methods offer the potential of extraction in high water environments thus minimizing the need for energy-intensive dewatering and drying.

Subcritical water (red lines) possesses properties similar to those of organic solvents enabling extraction of oils from mixed feed streams.

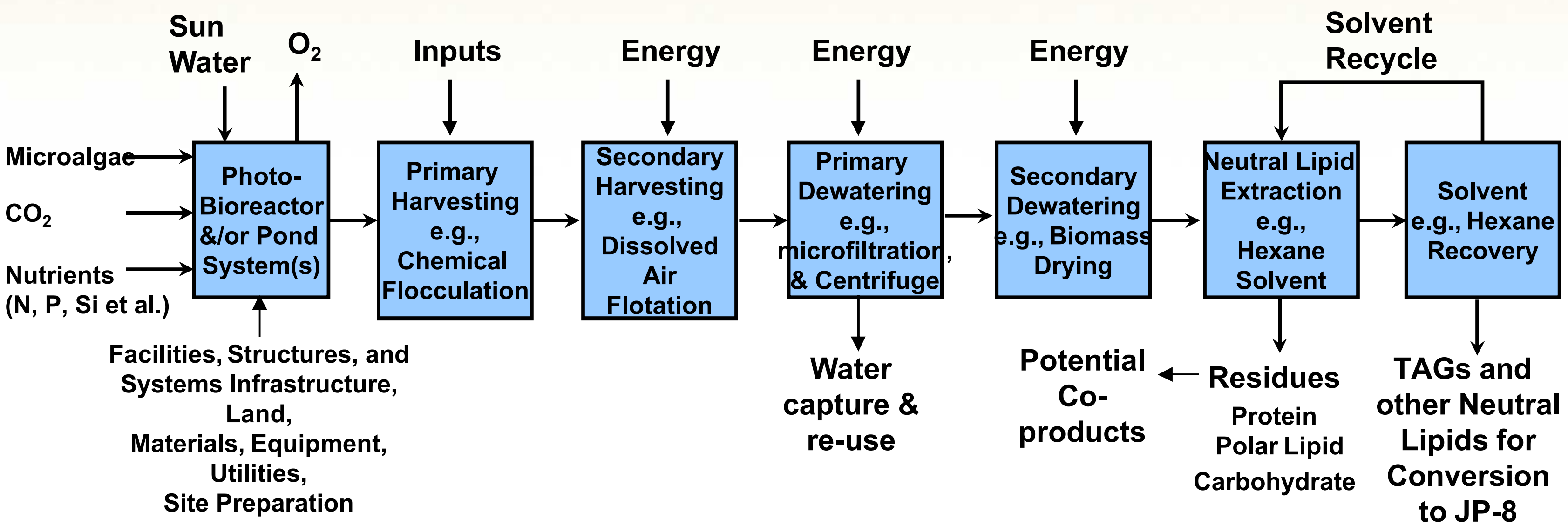




System Dynamics Decision-Support Modeling of Algal Biofuels Interdependencies



Baseline Cost/Performance Analysis Algal Oil Production Systems/Processes



Approach to microalgae oil production cost estimation

- Use Benemann and Oswald's economic analysis in 1996 PETC report (open pond) and more recent pond and PBR technical/economic analyses (e.g., Chisti (2007), Richmond (2004), Molina Grima, et.al. (2003), etc.) for background and comparison
- Develop mod/sim/analysis/LCA of overall system/process chain (diagram shown above)
- Apply unit operations and designs validated by data from outdoor development systems
- Apply scale-up and infrastructure build-up cost/benefit assessments
- Update economic analysis to reflect
  - Inflation
  - New unit operations
- Identify improvement opportunities with systems and processes through sensitivity analysis of multiple pathway options

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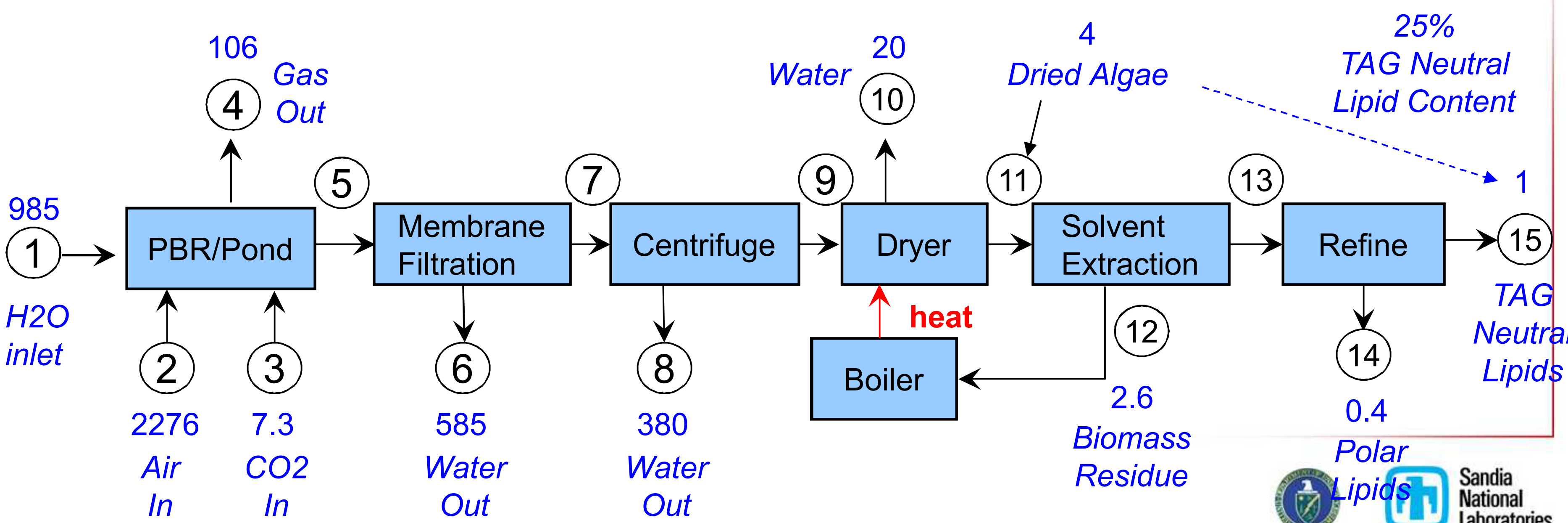
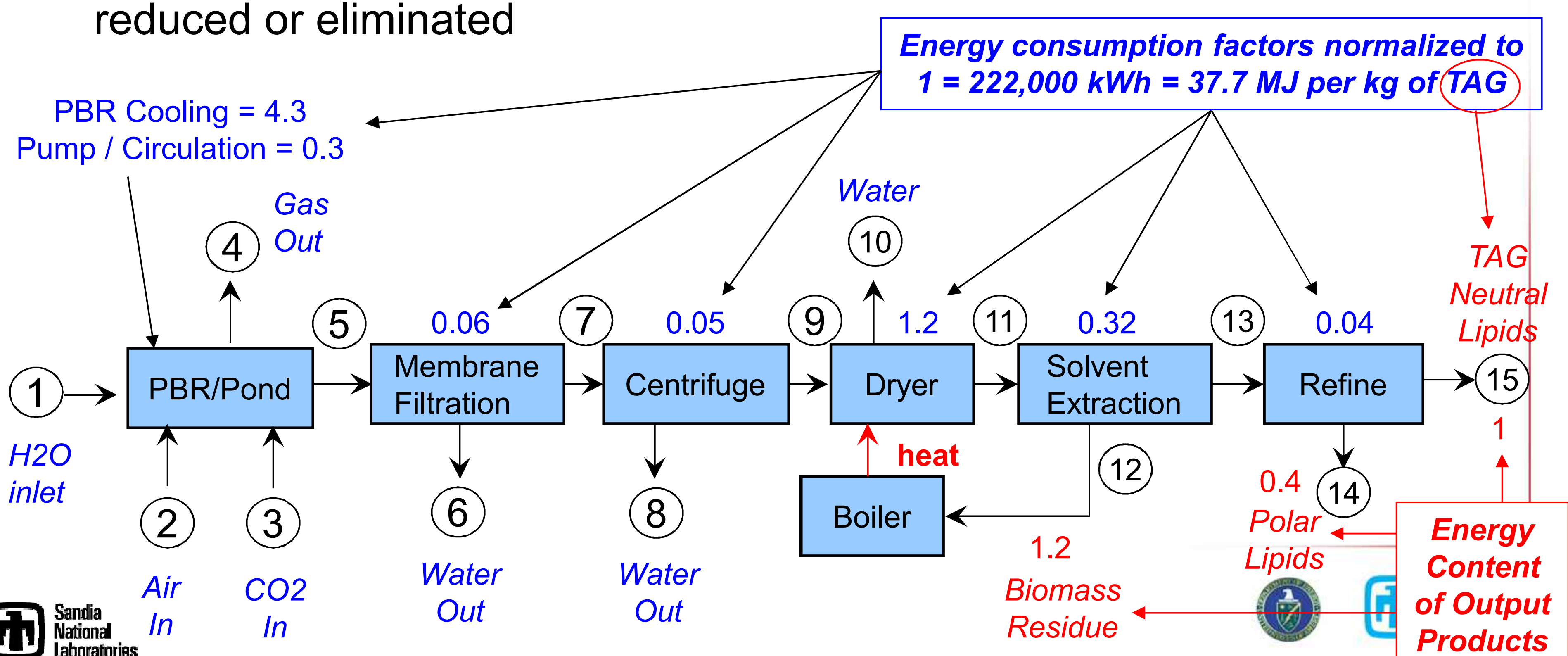
Preliminary Estimate of Algal Oil Production Mass Balance at Scale-Up to 50-Mgal/year

- Capture 75% carbon from 1 GW power plant in daylight
- 68 km^2 (16,796-Ac) to produce 50 million gallons/year of algal oil (TAG)
- Productivity ~2977 gal/Ac at 25% neutral lipid TAG content
- Significant evaporative water loss for cooling PBR ≥ 300:1 (H_2O:oil)
- Significant evaporative water loss with open ponds ≥ 300:1 (H_2O:oil)



Preliminary Estimate of Algal Oil Production Energy Balance at Scale-up to 50-Mgal/year

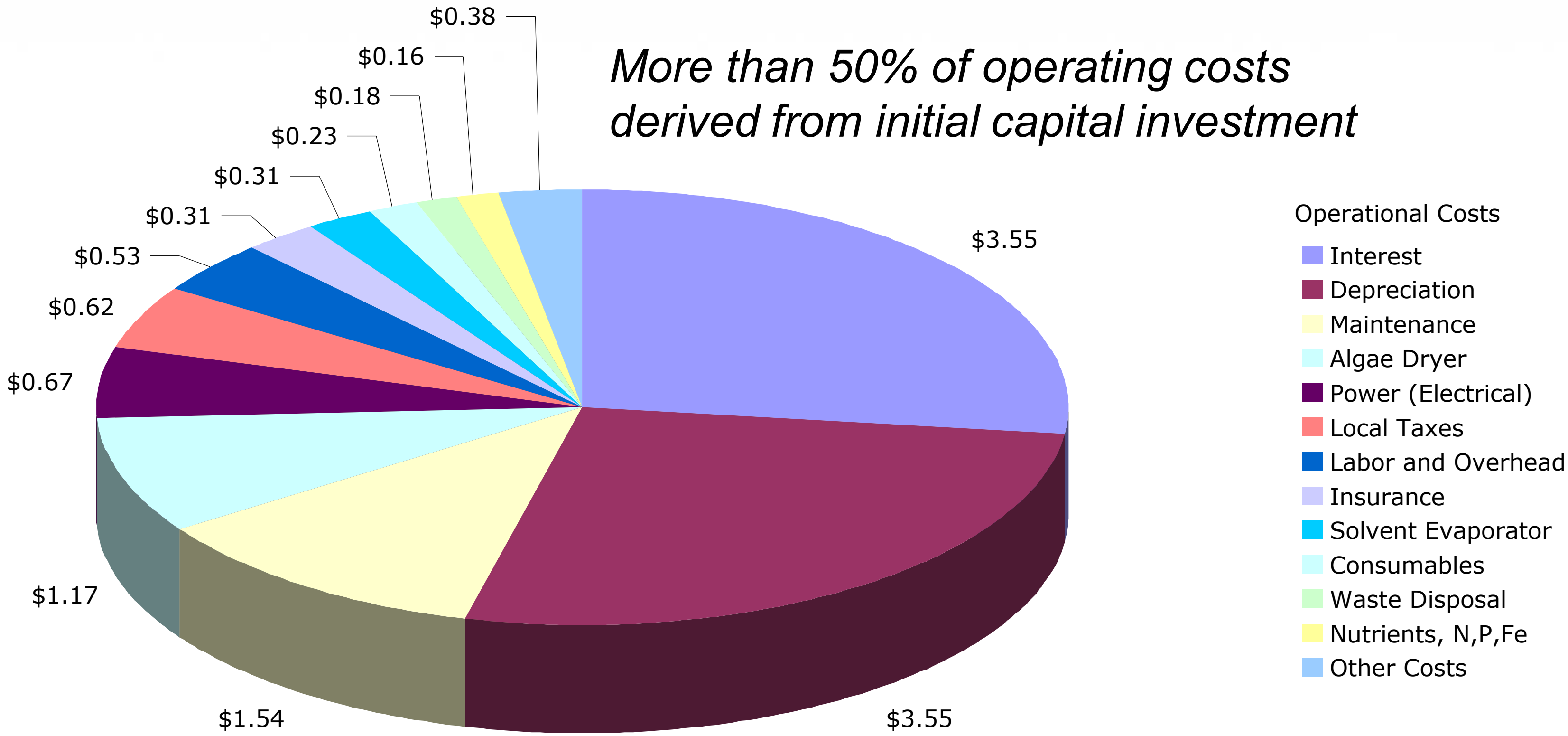
- Direct cooling of closed PBR with chilled water is too energy intensive
- Indirect cooling requires less energy but requires more water
- Energy for pumping/circulation is significant for open & closed systems
- Drying of biomass is too energy intensive and must be significantly reduced or eliminated



Total Cost and Cost Breakdown for Open Ponds

Rough Preliminary Estimate

More than 50% of operating costs derived from initial capital investment



Total Production Cost Average: $13.20/gal

With Approximate Cost Range of $9/gal to $17/gal

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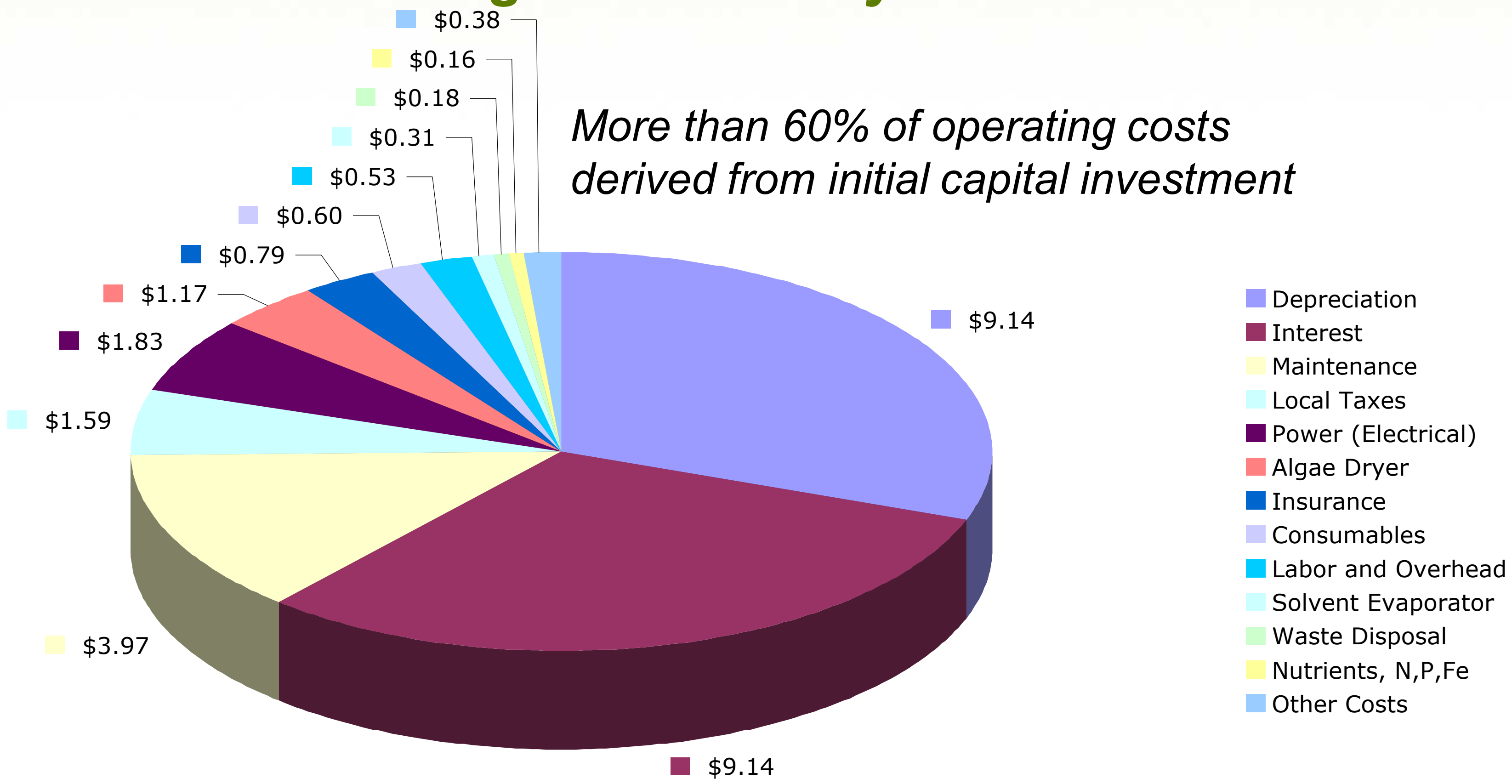
Total Cost and Cost Breakdown for Closed PhotoBioReactors

Rough Preliminary Estimate

More than 60% of operating costs derived from initial capital investment



Total Production Cost Average: $29.22/gal

With Approximate Cost Range of $20/gal to $38/gal

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Comparative Cost Assessment
Selected Sources for Algal Oil Cost Analysis

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

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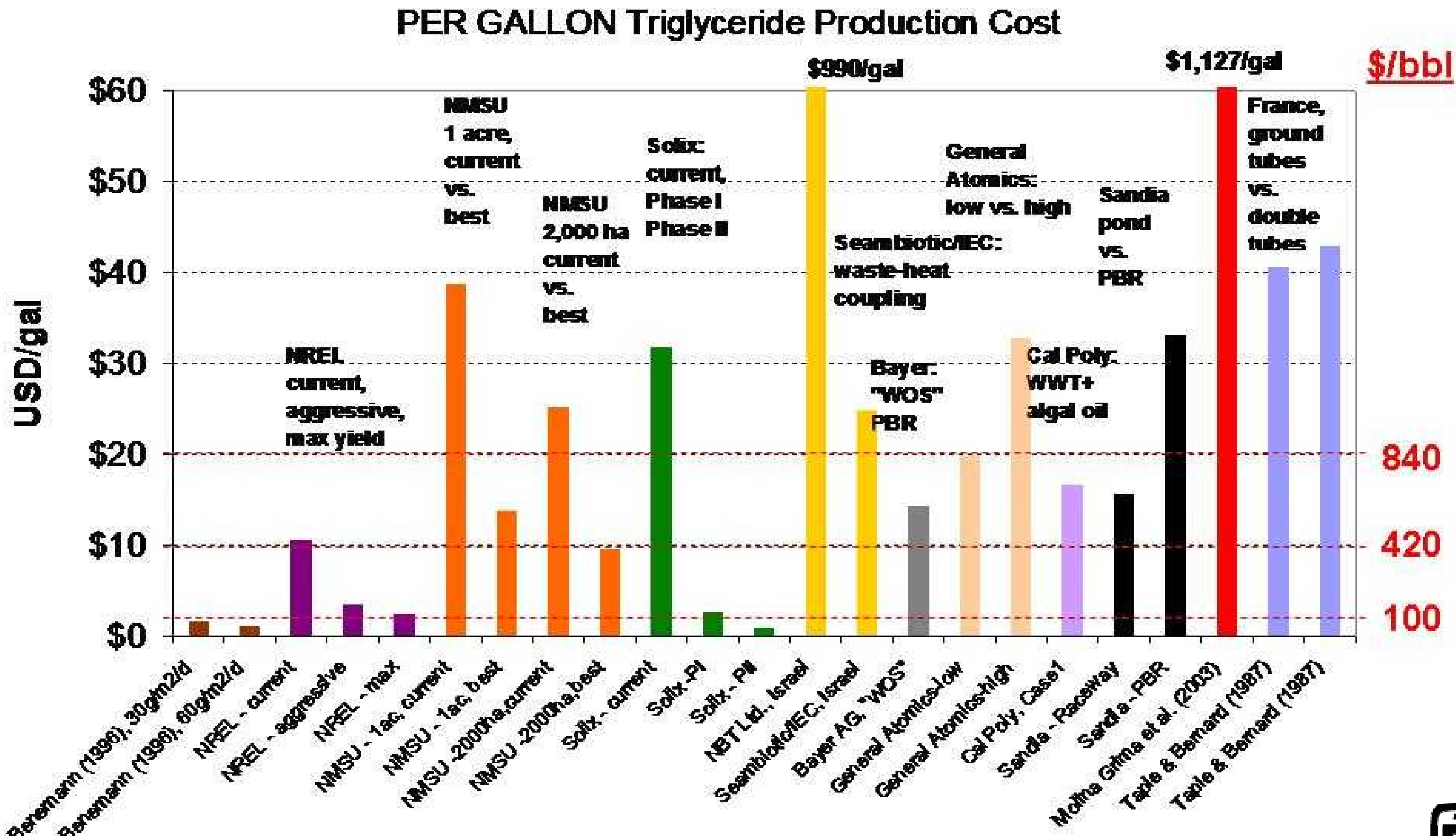
Wide Variance in Algal Oil Production Costs

Innovation Needed to Enable Commercial Feasibility

Standardized Algal Oil Cost Comparison

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



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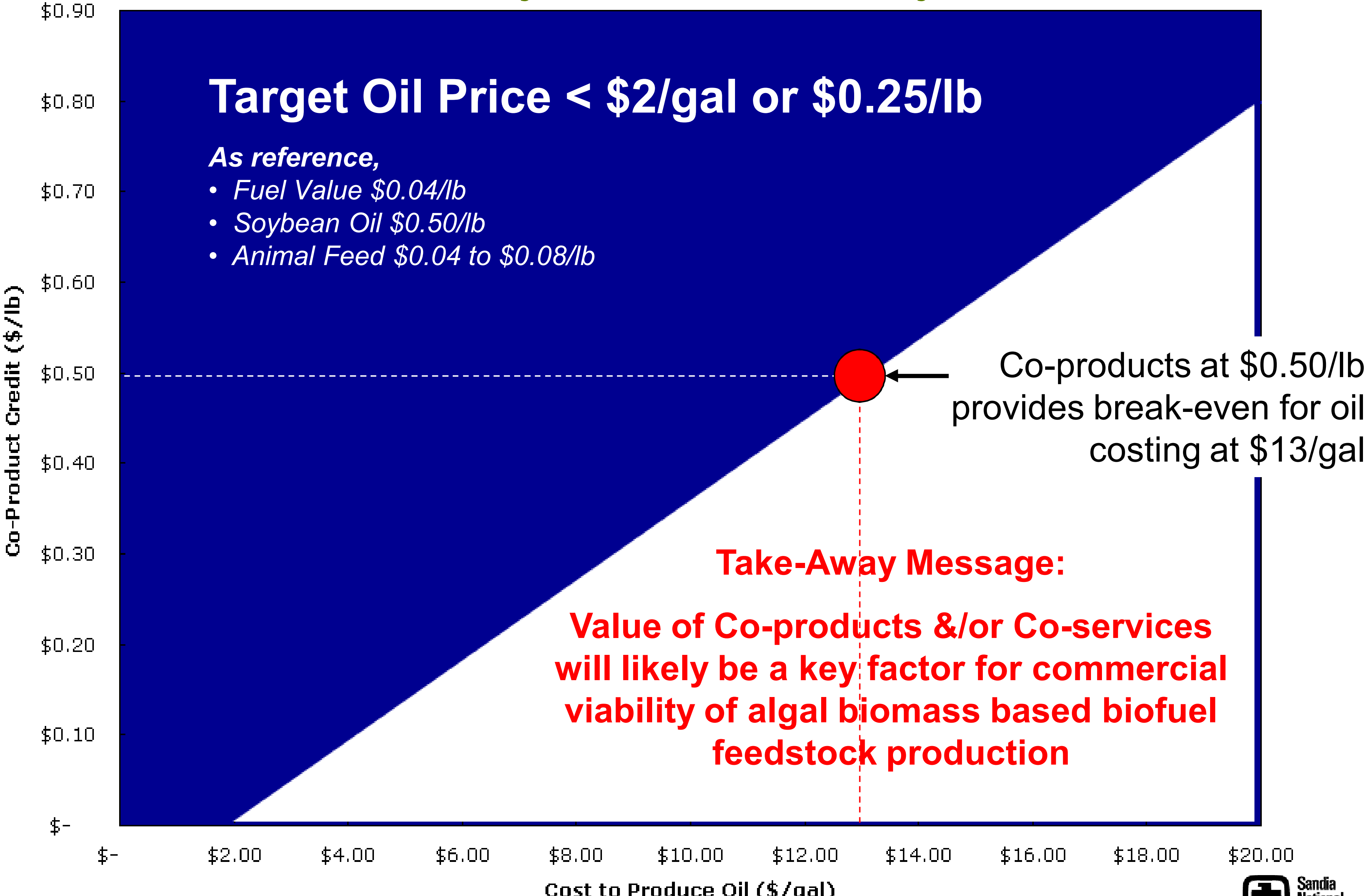
Value of Co-Products / Co-Services

… key to economic viability



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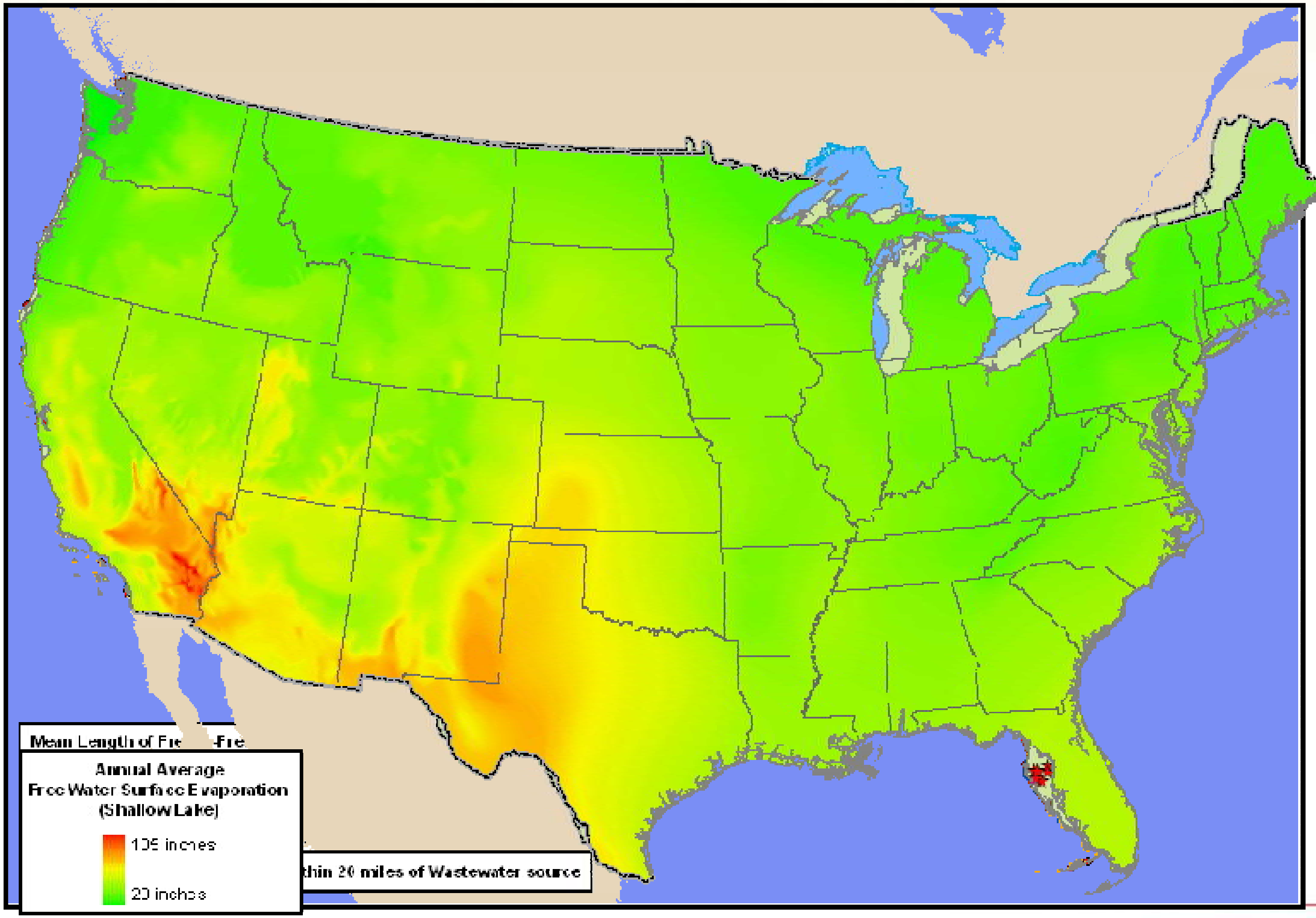
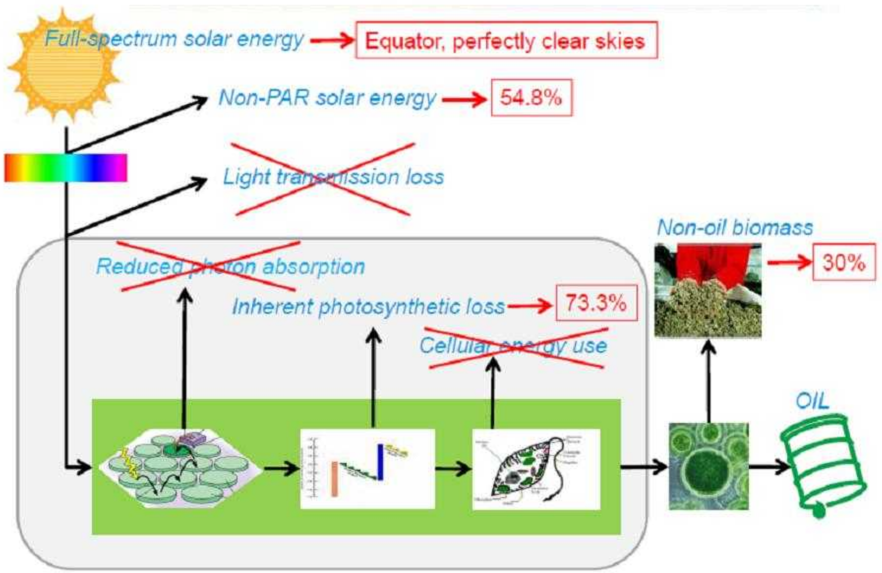
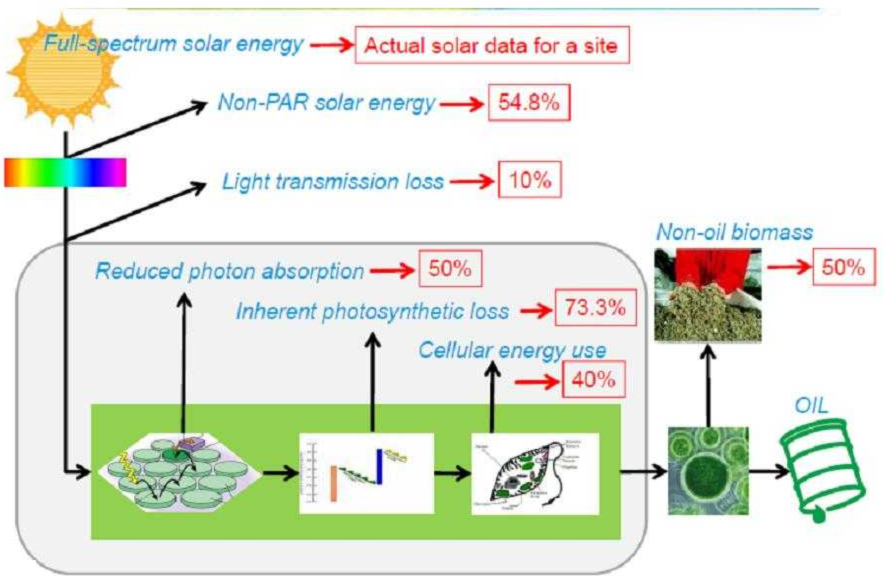
Initial Look at Preferred Siting of Inland Algal Biomass Production Facilities



Theoretical Case

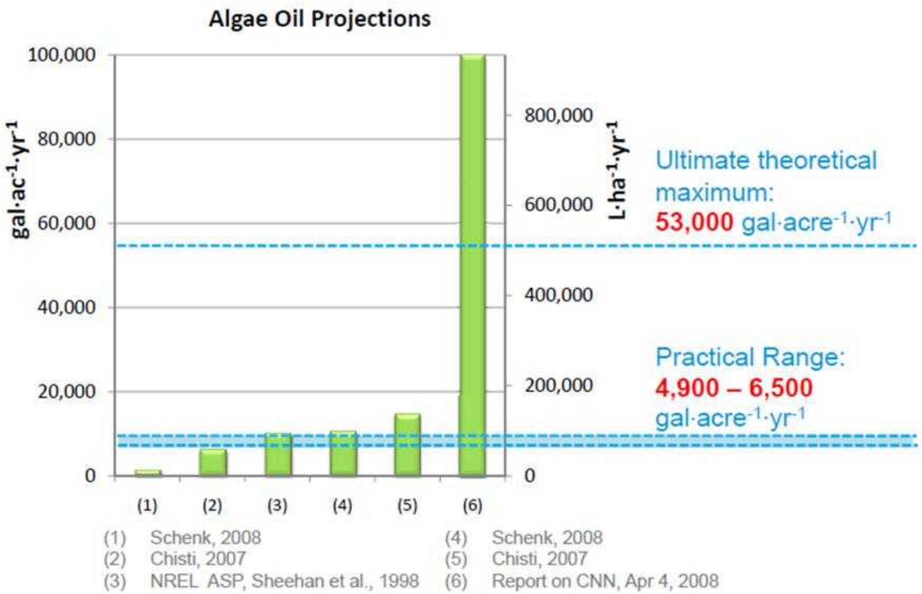


Practical Case



Apply Reality-Check on Algal Oil Production

Conclusions



Analysis and illustrations courtesy of **Kristina Weyer***
Solix Biofuels, Inc.
kristina.weyer@solixbiofuels.com

* *"Theoretical Maximum Algal Oil Production"*
2008 Algae Biomass Summit, Seattle, WA

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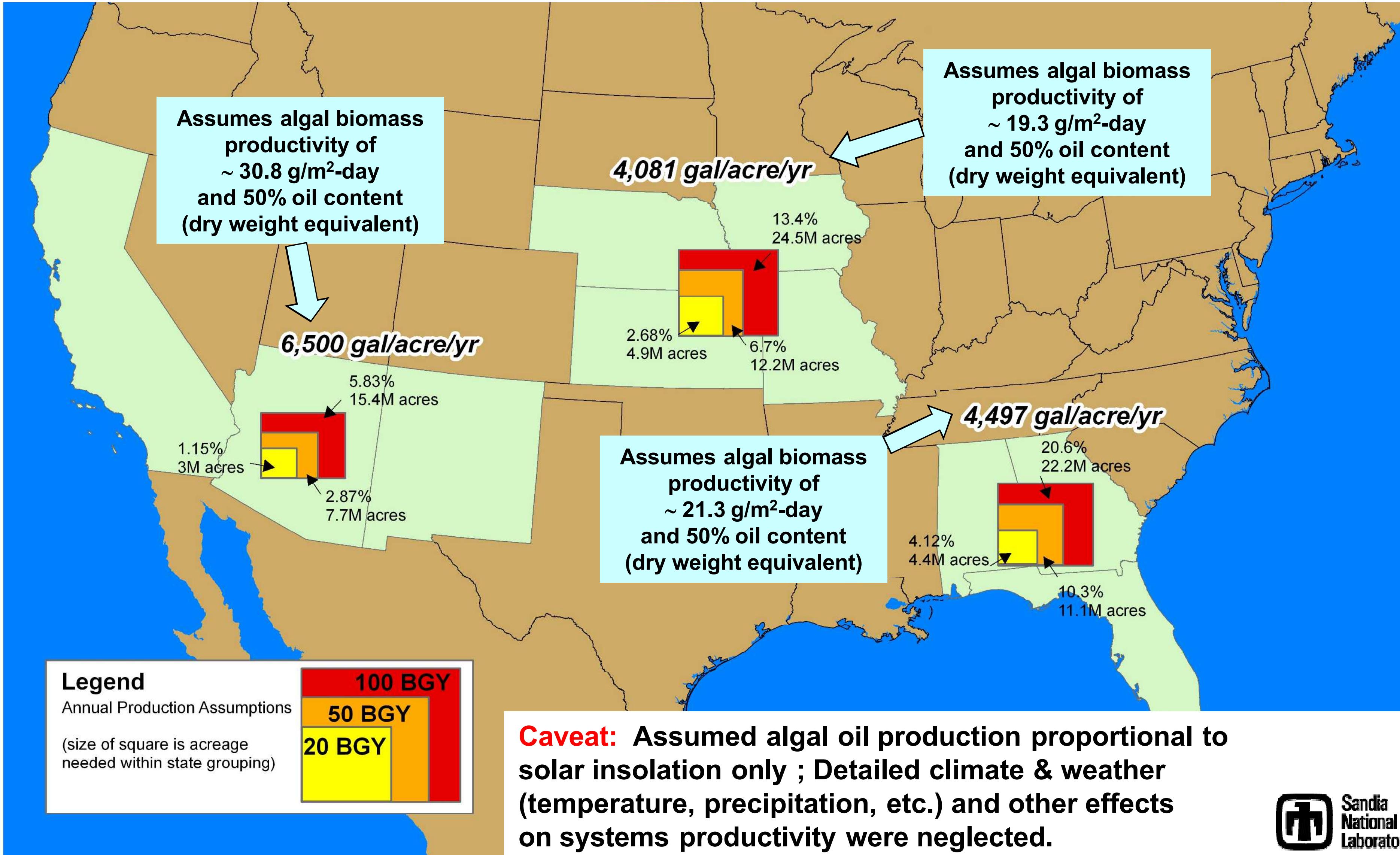
Three "Notional" Scale-Up Scenarios Considered for Initial Look at Algal Biofuel Production

Siting & Resource Requirements and Implications



Caveat: **Assumed algal oil production proportional to solar insolation only ; Detailed climate & weather (temperature, precipitation, etc.) and other effects on systems productivity were neglected.**

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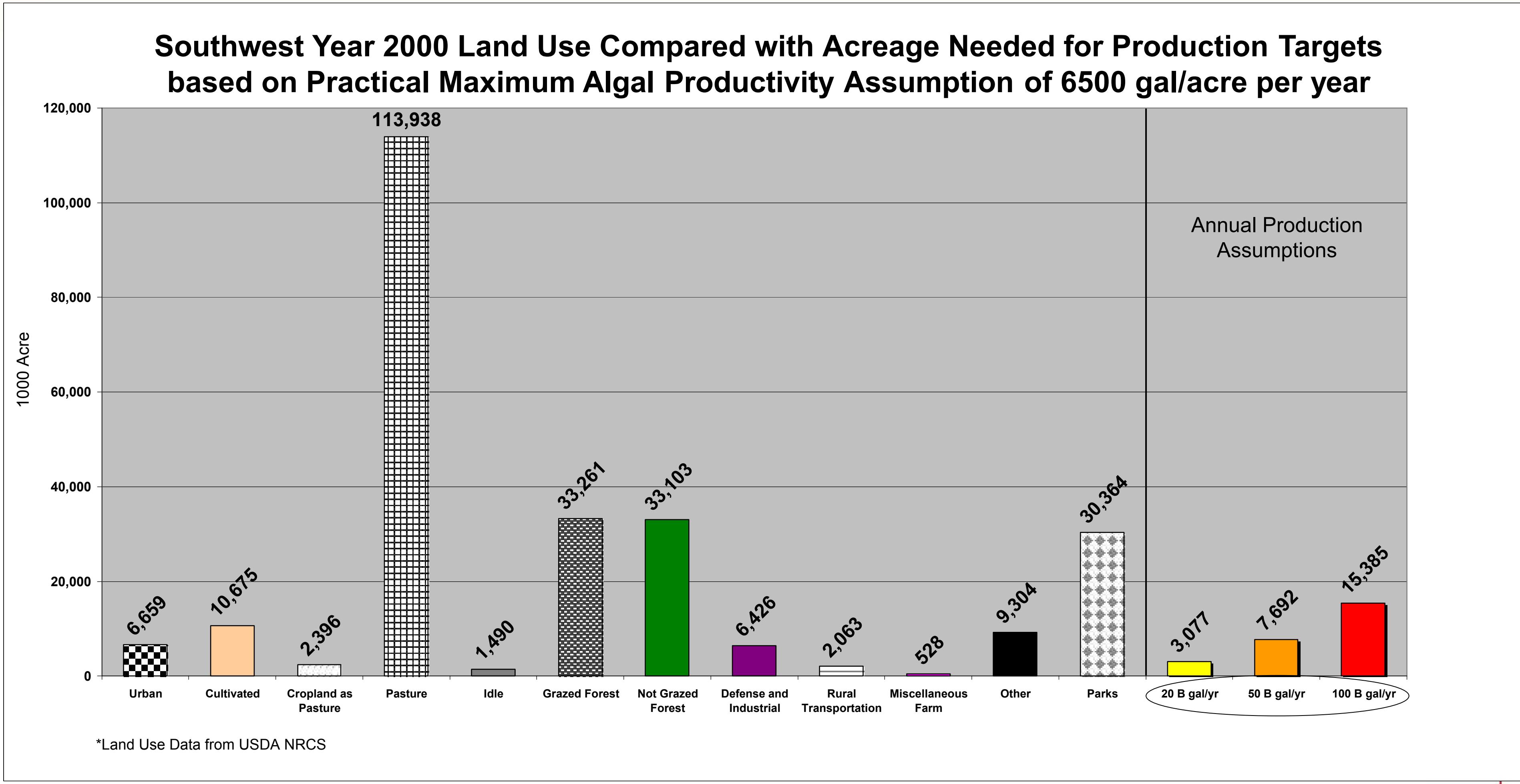
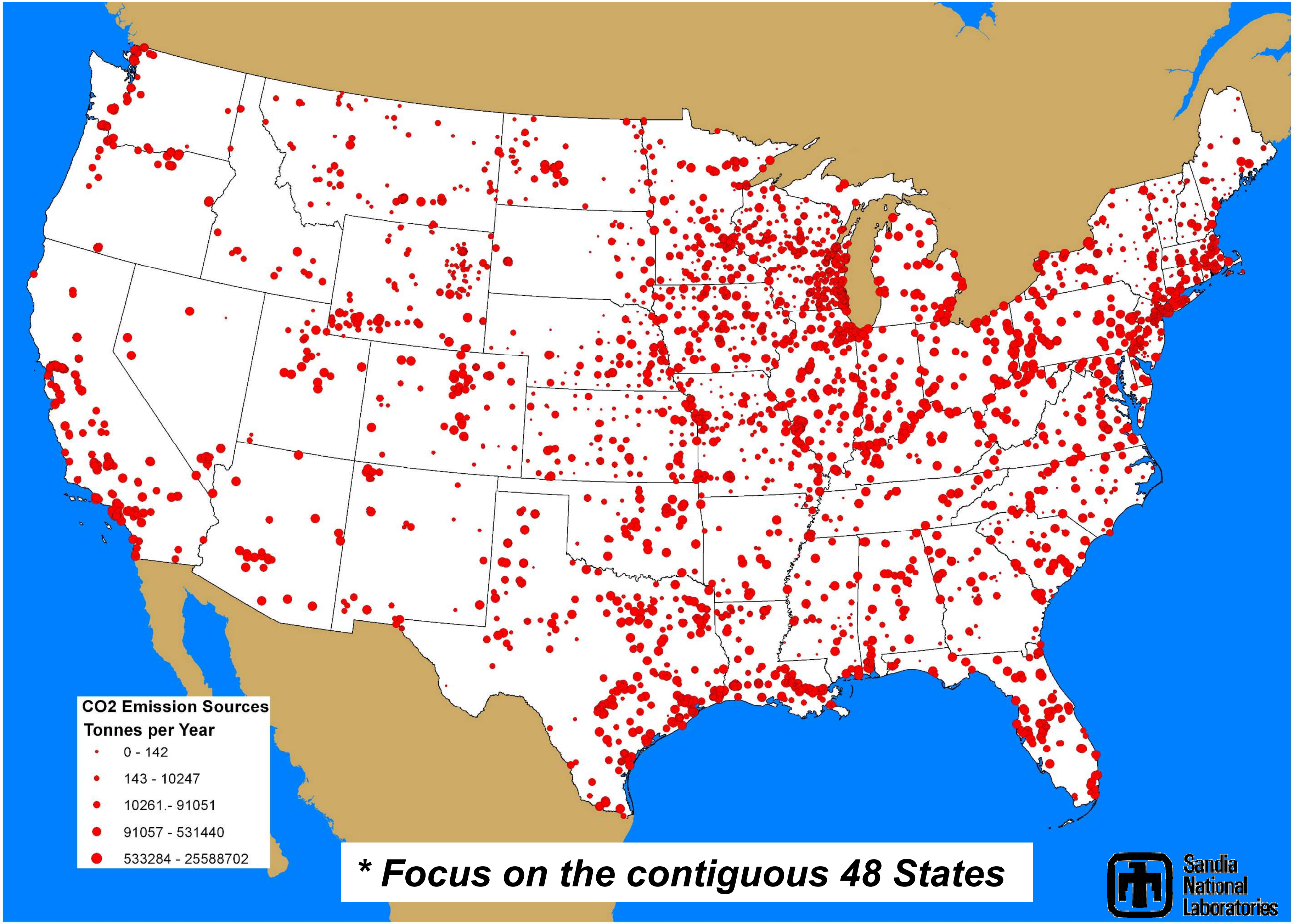
Southwest Region Scenario Land Footprint Consequences Compared with Land Usage*



*** Total Combined Land by Category in CA, AZ, and NM***

Factor in US* Distribution of CO_2 Sources



***Focus on the contiguous 48 States**

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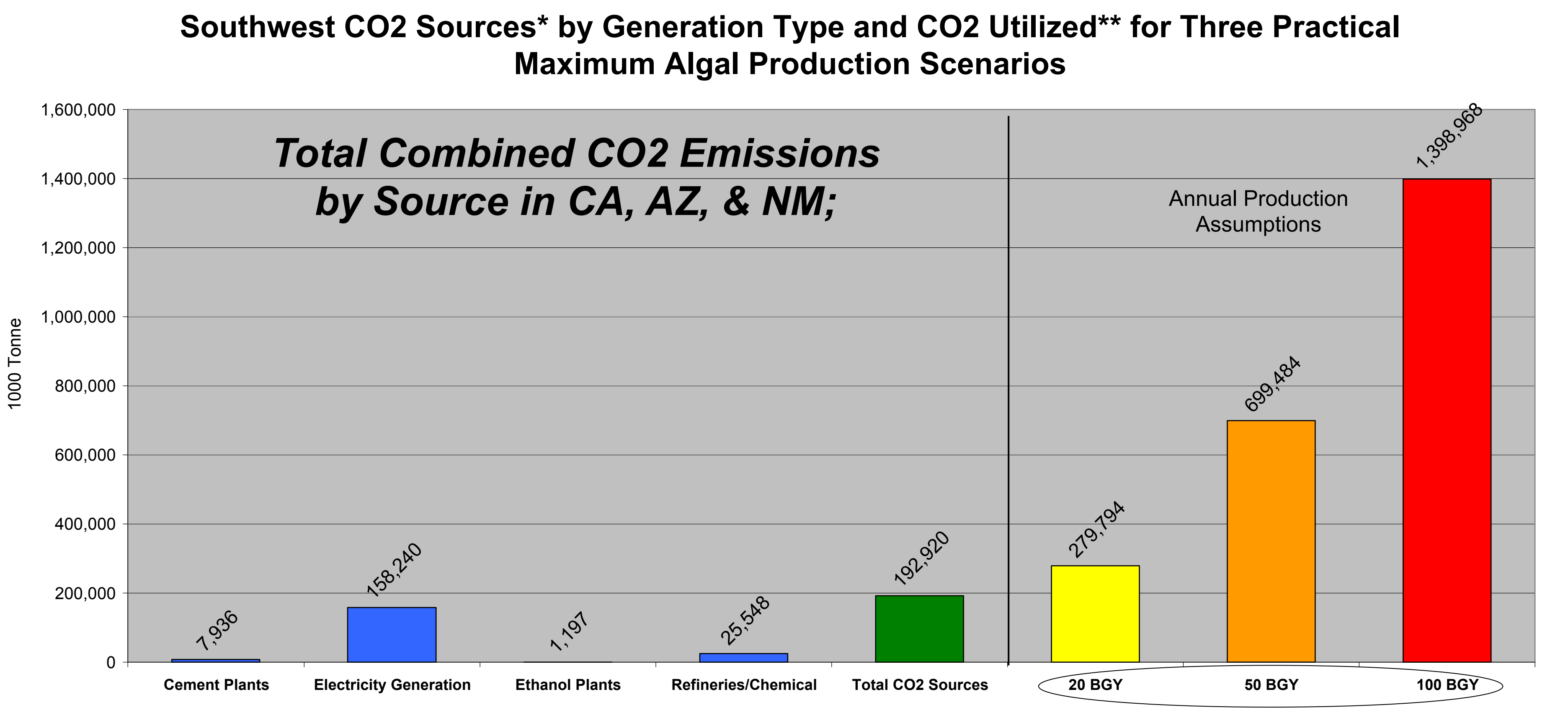
Identified Stationary CO_2 Sources from *NATCARB 2008 Stationary CO_2 Source Atlas*

http://www.natcarb.org/

CATEGORY	**CO_2 EMISSIONS Million Metric Ton/Year**	**Number of Sources**
Ag Processing	6.3	140
Cement Plants	86.3	112
Electricity Generation	2,702.5	3,002
Ethanol Plants	41.3	163
Fertilizer	7.0	13
Industrial	141.9	665
Other	3.6	53
Petroleum and Natural Gas Processing	90.2	475
Refineries/Chemical	196.9	173
Total	**3,276.1**	**4,796**

Southwest Region Scenario CO_2 Usage Consequences vs. CO_2 Source Constraints

(*Total US* CO_2 Emissions* ~ 3.28 billion metric tonnes**)



Note: CO2 utilization estimate assumes 4-lbs of CO2 consumed for every 1-lb of algal oil (TAG) produced, based on 50% oil content of algal biomass (dry weight) and 7.7 lbs per gallon of oil

**** Focus on the contiguous 48 States***

***** NATCARB 2008 Stationary CO2 Source Atlas***

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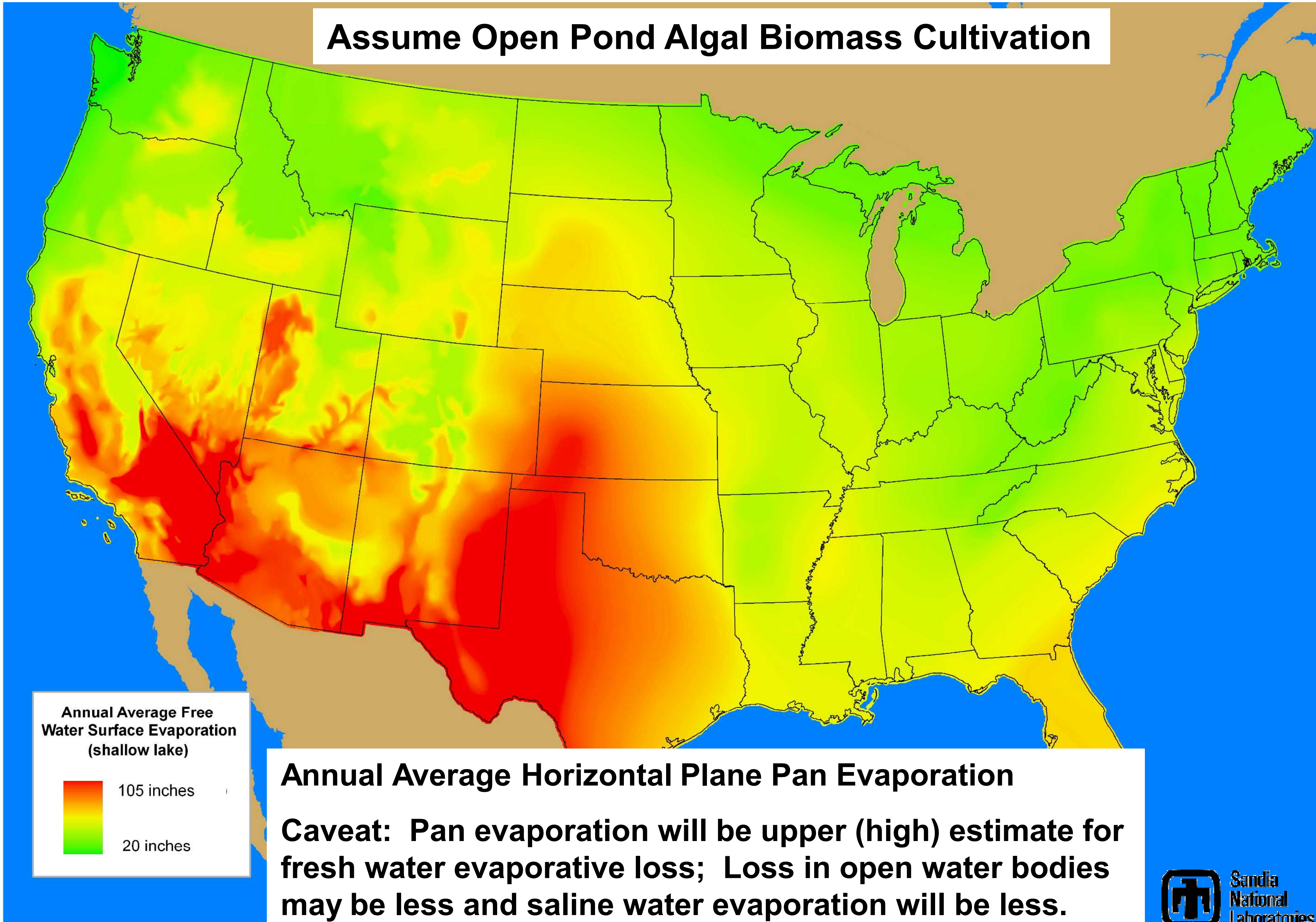
Factor In Evaporative Water Loss

Assume Open Pond Algal Biomass Cultivation



Annual Average Horizontal Plane Pan Evaporation

Caveat: Pan evaporation will be upper (high) estimate for fresh water evaporative loss; Loss in open water bodies may be less and saline water evaporation will be less.

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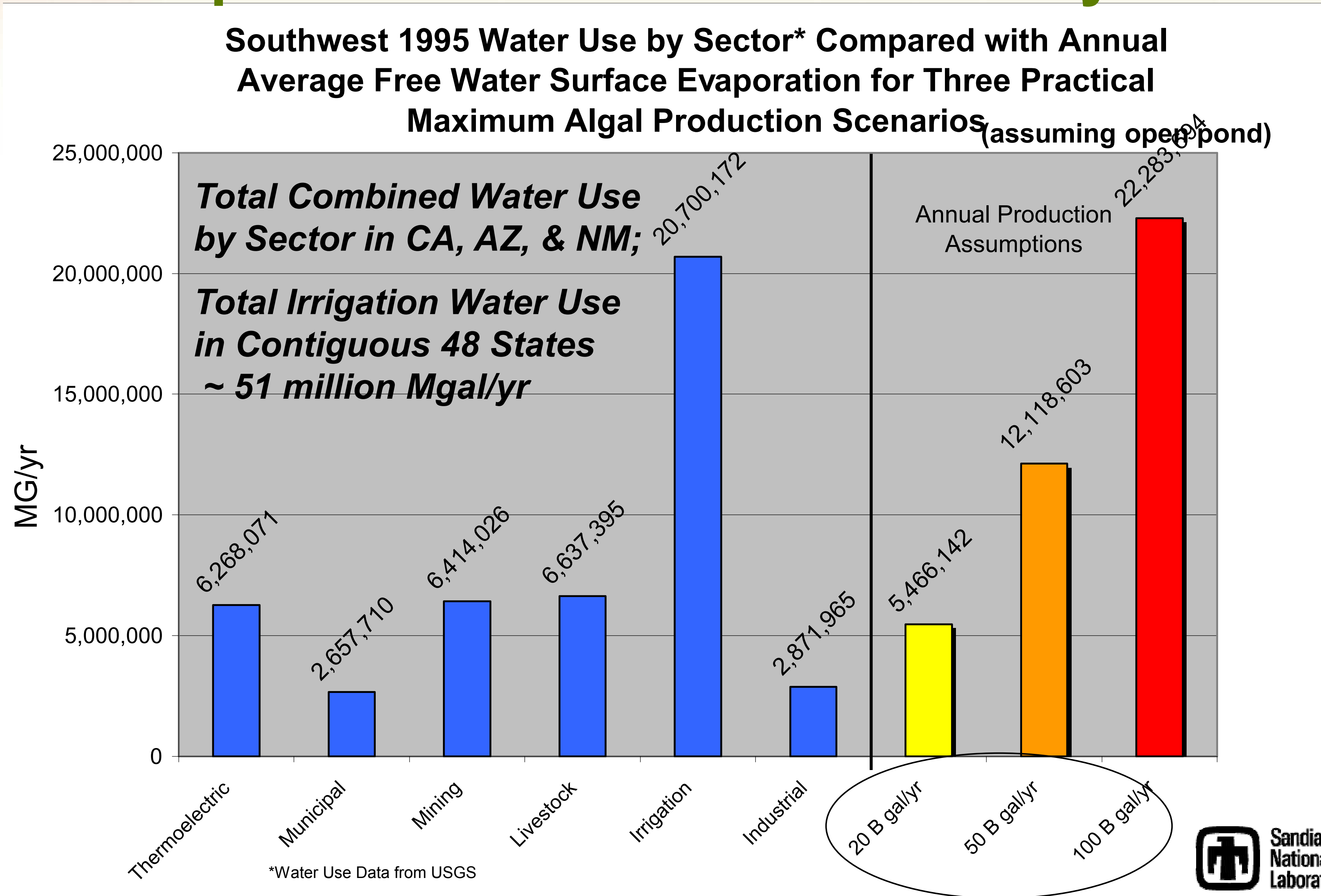
Southwest Region Scenario Water Loss Consequences vs. 1995 Water Use by Sector



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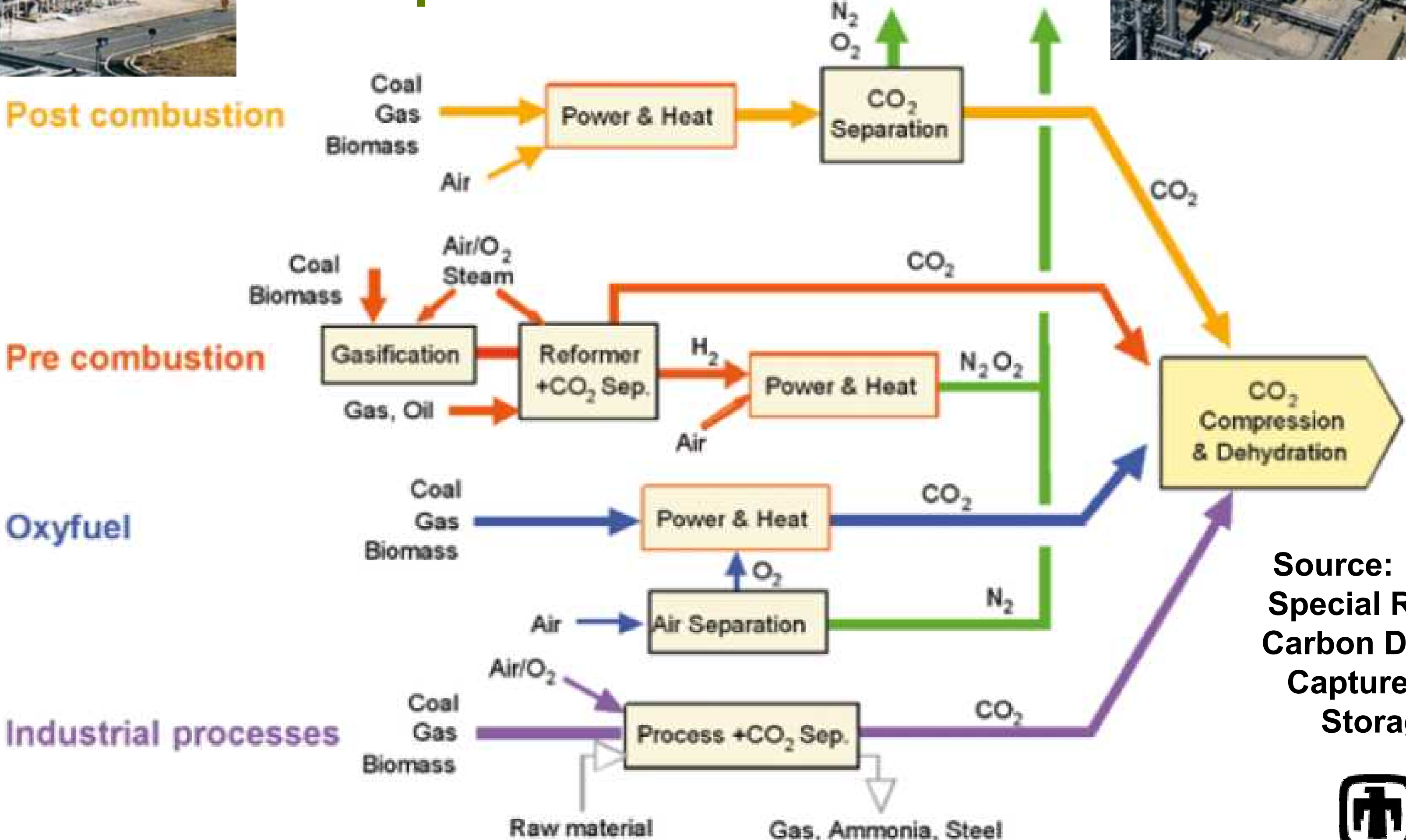
More Focus is Needed on Assessing the Cost and Logistics for CO2 Capture and Sourcing for Algae Biofuel Production… and Impacts of GHG Policies



Source: IPCC Special Report Carbon Dioxide Capture and Storage

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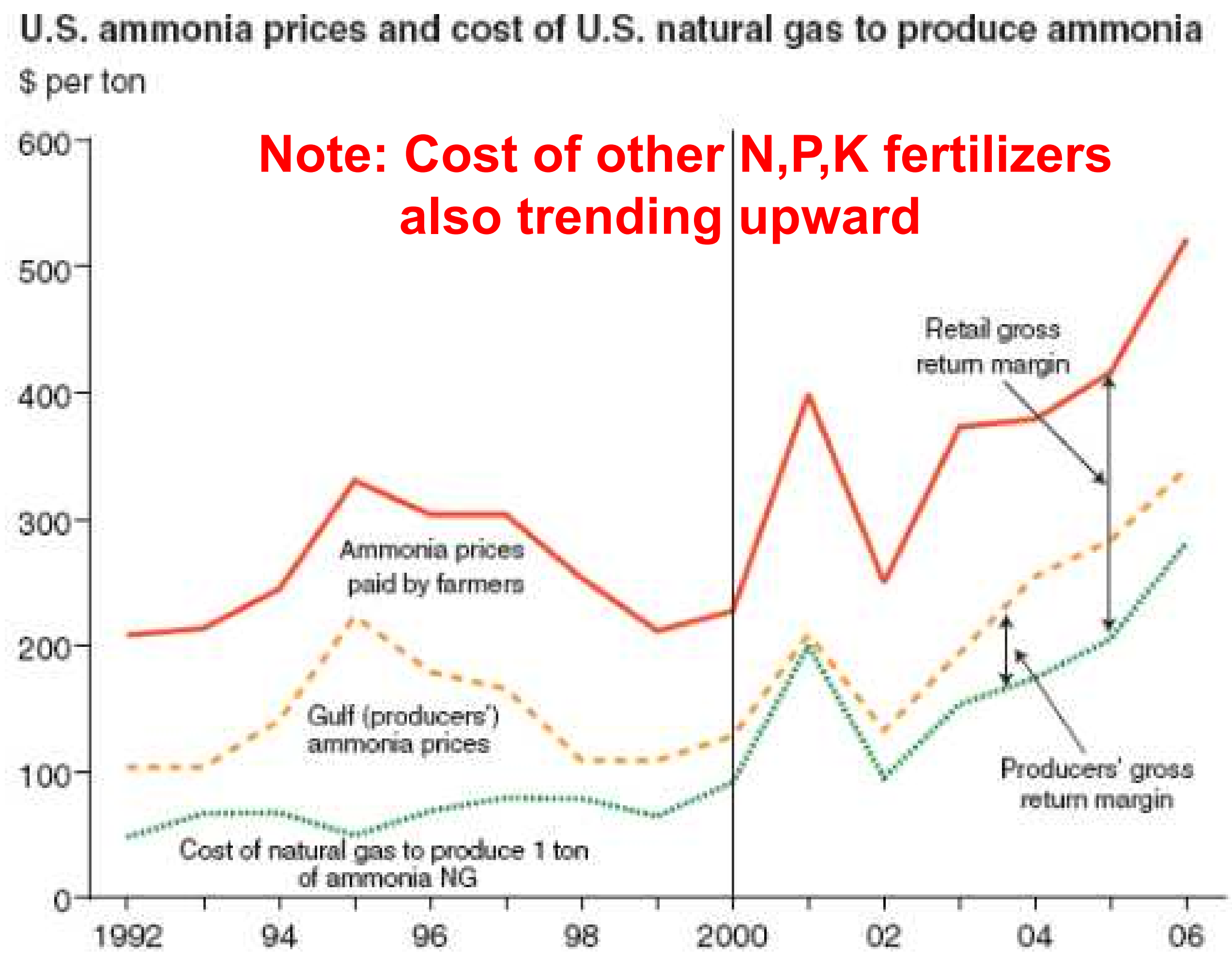
Scale-Up of Algae Biomass Production

Requires Other Nutrients (N, P, K)

Subject to Increasing Costs Linked to Energy and Imported Fertilizer Supplies



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).

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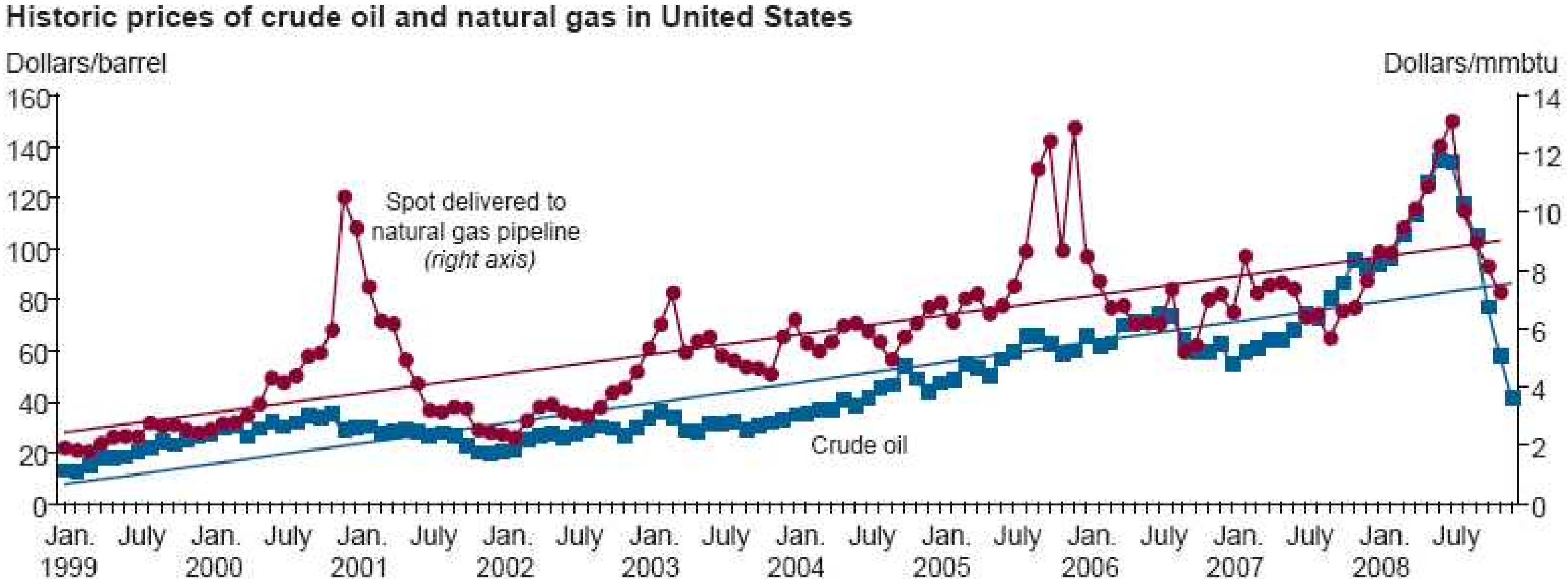
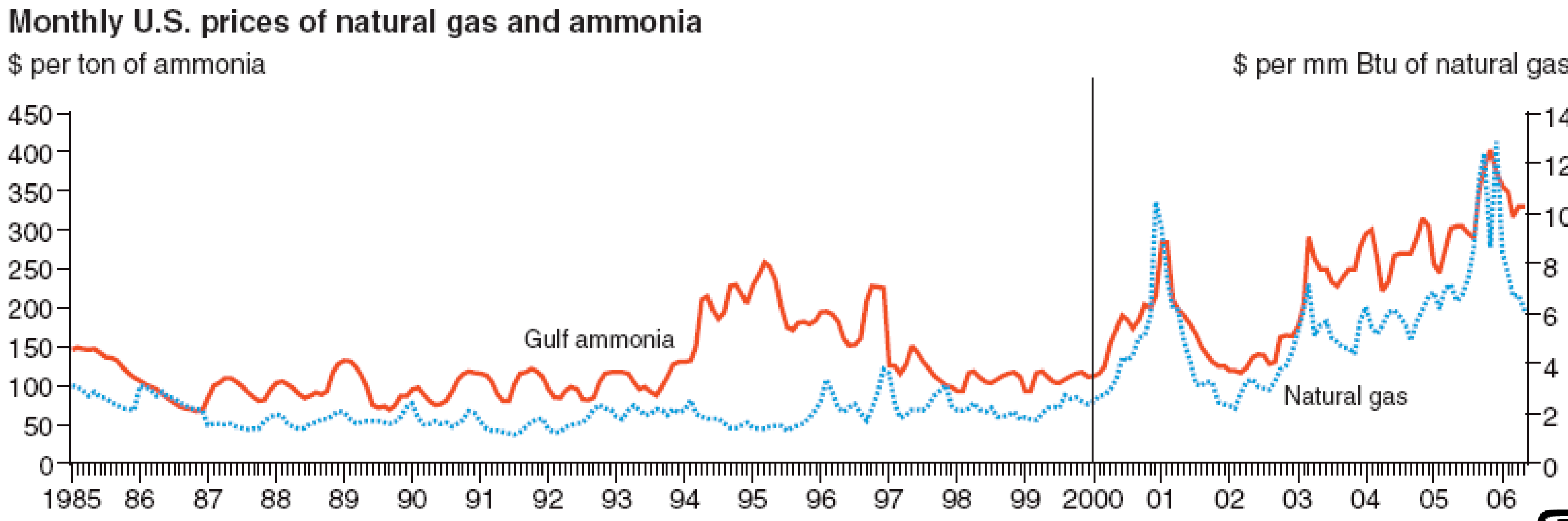
Ammonia Costs Track with Gas/Oil: Trending Upward



Note: mmbtu = million British thermal units.

Source: USDA, Economic Research Service using data from U.S. Department of Energy and The Fertilizer Institute.



Source: USDA, Economic Research Service using data from TFI (b).

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Summary Observations

- Land footprint required for national scale-up of significant algae biofuel production looks manageable.
- Water loss from inland open algae production systems is likely to be an issue for massive scale-up
- Need paths & approaches to mitigate water loss
  - Closed systems and location of open systems in less arid environments
  - Onshore coastal & offshore production options using ocean water
- CO_2 sourcing and distribution for algae is a key issue
- Availability and cost of other nutrients (N,P,K) is an issue
  - Need to exploit capture, recovery & reuse of nutrients from wastewater, etc.
- Salt & thermal management are inland systems issues
- Need to identify and exploit geographically-distributed opportunities for synergistic co-location of algae biofuels production with water treatment, power generation, and other co-product industries and markets
- Innovation needed in biology, systems and processes, and systems integration for commercial viability

Conclusions: Algal Biofuels

- Algal Biofuels of Significant Interest from Several Perspectives:
  - Energy/Fuel Availability & Security … National Security & Economic Benefits
  - Sustainable Scale-up and Resource Use (land, water, energy, nutrients, other)
  - Reduced GHG Emissions
  - Leverage of Existing Hydrocarbon Fuels Distribution & Use Infrastructure
- Potential for Very High Oil Feedstock Productivity with Non-Fresh Waters, Reduced Land Footprint, and CO_2 recycling
- Synergy with Waste Water Treatment and Industrial CO_2 Emitters
- Potential for Biofuel Scale-Up w/ Reduced Impacts on:
  - Fresh Water Supplies
  - Higher Productivity Agricultural Lands
  - Food/Feed/Fiber Markets
- R&D Needs & Opportunities
  Addressing Challenges with Biology, Systems, & Processes to Enable…
  - Cost-effective, commercially-viable feedstock & fuels production scale-up
    - Technologies, Processes, Systems
    - Systems Integration and scale-up
  - Sustainable resource utilization (Energy-balance, water-balance, nutrients, net GHG emissions, productive use of waste streams, etc.)
  - Thermal management & salt management are issues/concerns
  - Co-products & Co-services

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DOE Algal Biofuels Technology Roadmap

Draft Report in Progress as of May 2009

U.S. Department of Energy
Energy Efficiency and Renewable Energy

Biomass

Objective

- To identify and prioritize key biological and engineering hurdles that must be overcome achieve cost-effective production of algal-based biofuels and co-products and suggest research strategies to address these key barriers such as process integration, reducing production costs, and improving efficiency and overall yields in a biorefinery-like environment.

Product

- A written roadmap to achieving scalable algal biofuels and co-products by 2020 with specific technical challenges identified, prioritized and presented in a Gantt chart project management plan.
- The challenges will be categorized with regards to the science and engineering R&D required and reduction-to-practice content.
- The relevance to the various elements of the US R&D enterprise, industry, and sectors of the US economy will be called out.
- The resulting DOE Algal Biofuels Technology Roadmap will be made available to the general scientific community. Currently in draft form; Expected to be released for public comment May 2009.

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NREL

http://www.orau.gov/algae2008/resources.htm

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