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ENG 505 - ENERGY SURETY AND SYSTEMS

Alternative Fuels

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SANDIA REVIEW & APPROVAL NUMBER

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Outline of Presentation

- Brief Biographical Note of Presenter(s)
- Alternative Fuels Technology in Context of Complex E-W-L-Climate Nexus
- Fundamental Concepts and Representative Approaches to Alternative Fuels
- Current Applications and DOE Program R&D Activities
- Sandia Capabilities (wrt Alternative Fuels)
- Challenges and Opportunities
- Examples of Complex Systems Aspects of Alternative Fuels
- Conclusions Summary
- Question & Answer Session

Brief Biographical Note of Ron Pate

- Educational Background
  - 1971: BS, Engineering Physics, University of Arizona-Tucson
  - 1978: MS, Electrical Engineering, University of Colorado-Boulder
- Professional Experience in Energy Industry
  - 1978-80: Geophysicist, Shell Oil Company, Houston, TX
  - 1982-86: Advanced Ignition Systems Research Manager, Star Hill Co., Albuquerque, NM
- Sandia Experience/Career Highlights Summary … 26 years at Sandia
  - 1986-88: Lead Electrical Design & Diagnostics, MITL System, HERMES-III Accelerator
  - 1988-90: Strategic Arms Control Tagging Systems R&D
  - 1990-95: Renewable Energy Systems R&D, PV Design Assistance Center, USAID-Mexico
  - 1995-2001: Project Lead, Directed Energy-High Power Microwave Project with AFWL
  - 2001-2004: Advanced Concepts Group
  - 2004-2006: Energy-Water-Ag Interdependencies, Energy-Water Roadmap, Biofuels R&D
  - 2006-2008: SNL Lead for DARPA Biofuels Project with UOP Team
  - 2008-2009: Core team for Development of DOE/EERE-OBP Algal Biofuel Technology Roadmap
  - 2009-2011: Temporary 2-year Assignment with DOE/EERE-OBP, Wash DC, Algae Biofuels Team
- Current Sandia Projects
  - Renewable Energy / Smart Grid Projects: Mesa del Sol, Hawaii
  - National Climate Assessment Technical Report Team: Energy-Water-Land-Climate Nexus
  - Deputy Director, National Algae Biofuels Testbed Proposal Team ATP^3 (led by ASU)

Recall: What is a Complex System?

- A **complex system** is a system composed of interacting elements that as a whole exhibit one or more properties (behavior among the possible properties) not obvious from the properties of the individual parts
- Common Attributes
  - Multiple interacting phenomena
  - Heterogeneous element
  - Non-linear dynamics and effects
  - Adaptive behavior
  - Elements with memory
  - Large network of elements or nested complexity

Recall: Approaches* to Complex Systems

- Mathematics
- Physical-Cyber-Behavior
- Threat and Risk
- Systems Engineering
- Sandia Software Tools
- Sandia Disciplines

These represent approaches or resources that an analyst or engineer may apply to a systems engineering challenge. They are not intended to be a complete set, just one chosen to add structure to this course.

*Note: These approaches represent a simplified set of complex systems concepts chosen for the ENG505 systems lectures. Please see the initial two systems lectures for additional detail and expanded references.

Complex Systems Engineering*

- This approach represents a number of methodologies all which usually have four simple steps to solve systems issues!
  1. Describe the system
     - Identify the elements of your system
     - Identify the interactions between the elements
       - Identify what flows over the interactions
  2. Describe system requirements
     - Safety, reliability, security, scalability, extensibility, manageability, maintainability, interoperability, sustainability, composability, adaptability, survivability, affordability, understandability, and, agility.
  3. Identify aspects for complex systems
     - Emergence, Complexity and Information, Dynamics and Self-Organization, Networks
  4. Apply one or more methodologies
     - Theory, Tools, and Approaches
     - Example: CASoS

*Note: Additional detail and expansion around other approaches are included in the initial two ENG505 systems lectures. This is only a simplified template summary for use in ENG505 energy-focused classes.

Complex System Context for Alternative Fuels

The Energy-Water-Land-Climate Nexus

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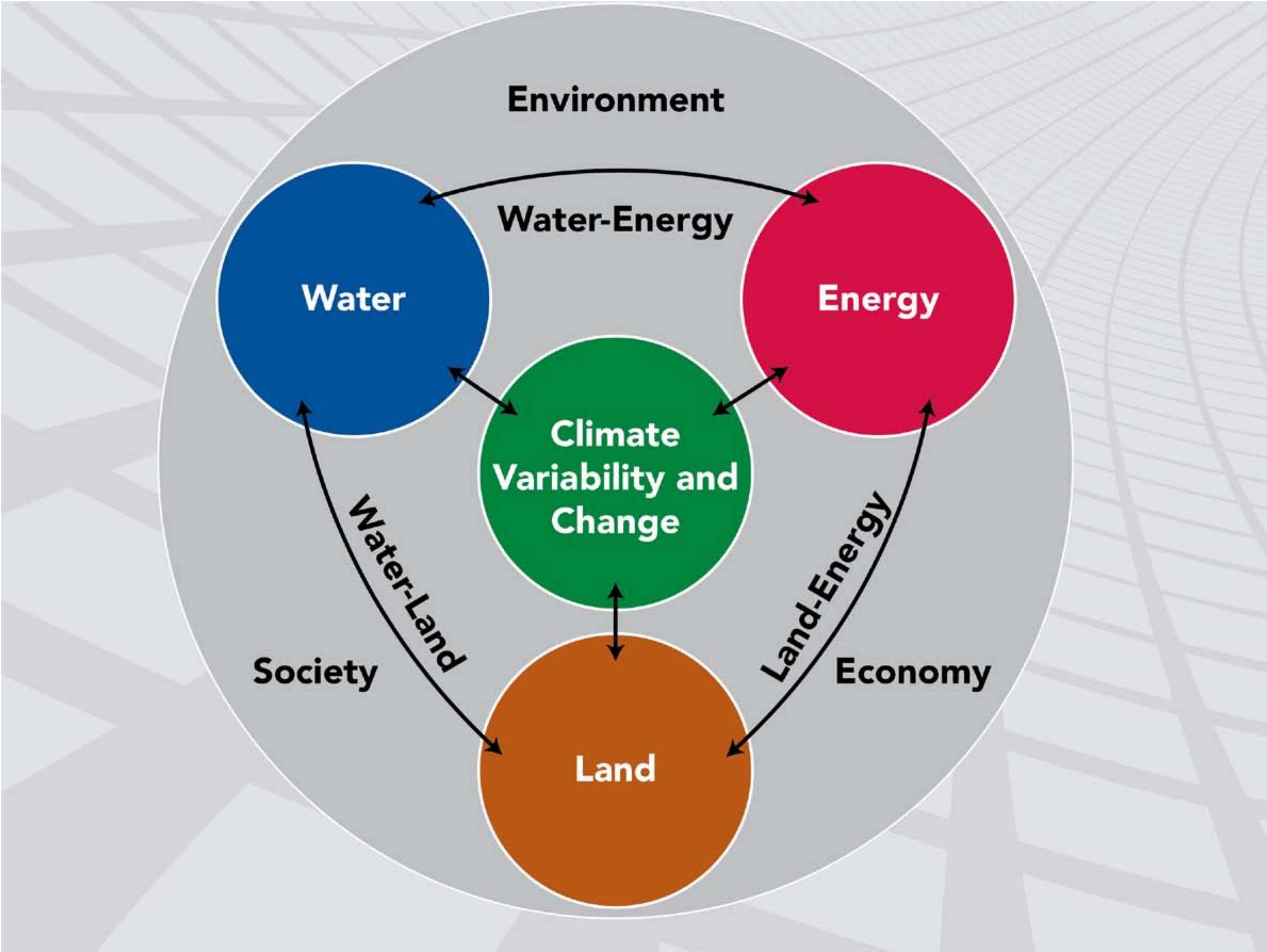


LAND FOR WATER
- Water-Capture & Watershed
- Ground Cover Vegetation
- Hydro-Geology
- Ecosystems

LAND FOR ENERGY
- Infrastructure
  - dams/reservoirs
  - mines/wells
  - power plants
  - solar & wind farms
  - power lines
  - pipelines
  - railways
  - refineries
  - biomass feedstock & biofuels production
- CCS
- Energy Mineral Deposits

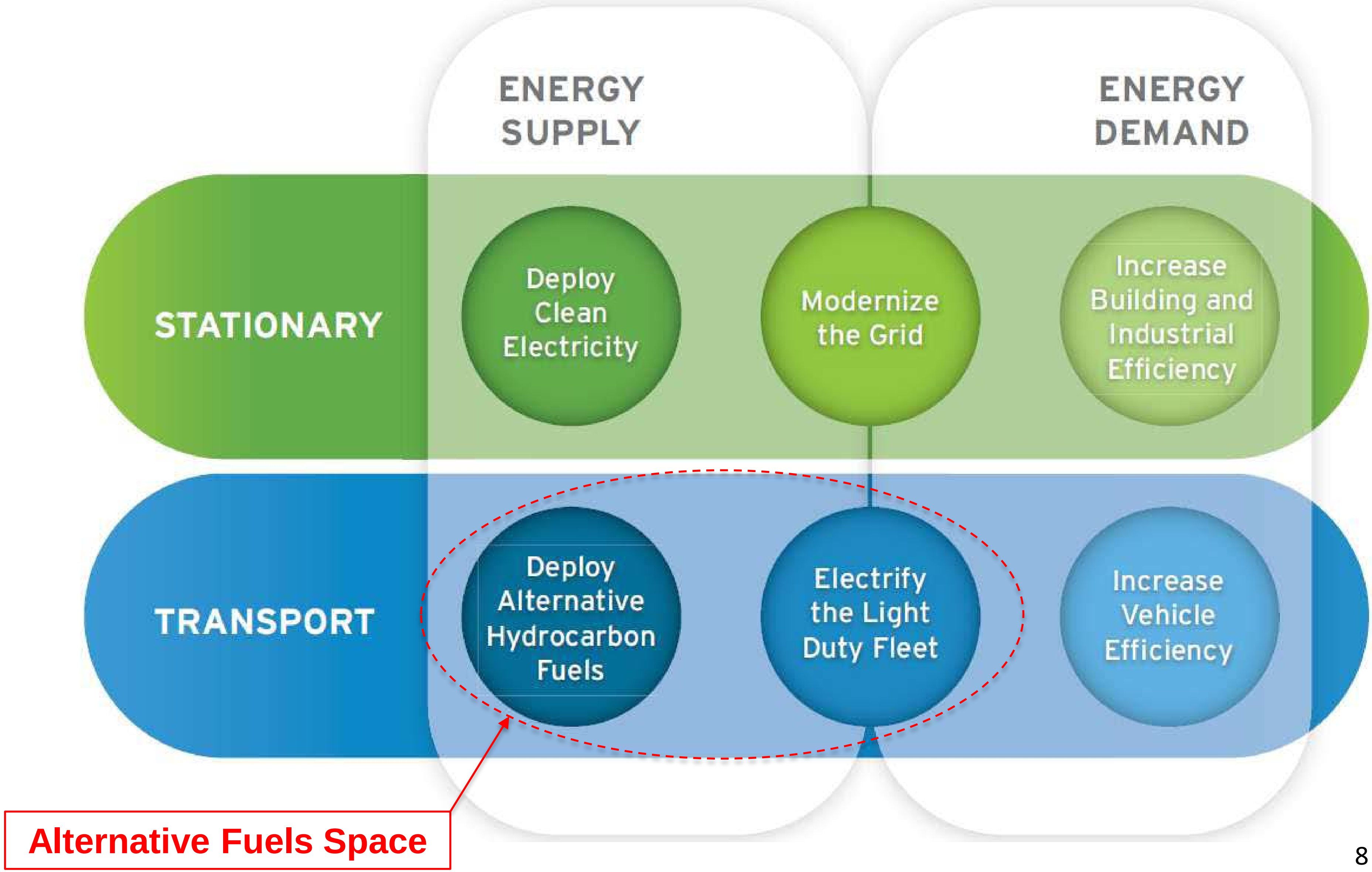
WATER FOR LAND
- Forests & Ecosystems
- Crop & Animal Agriculture
- Mining/Energy Extraction
- Industrial, Municipal, Commercial & Residential

WATER FOR ENERGY
- Extraction
- Cooling
- Processing
- Carbon Capture & Storage (CCS)

ENERGY FOR LAND
- Development
- Transportation
- Economic Productivity
- Resource Extraction & Conversion

ENERGY FOR WATER
- Pumping
- Transport
- Treatment
- Conditioning

Six Energy Strategies of DOE/EERE



DOE/EERE Goals*

** EERE FY13 Budget Request Roll-out Presentation by Henry Kelly, Acting Assistant Secretary, Feb 13, 2012*

Transportation

- Reduce oil imports 1/3rd by 2025 and diversify fuel mix:
  - Biomass – Less than $3/gallon (GGE) for drop-in fuels such as renewable gasoline, diesel, and jet fuel.
  - Cars able to achieve fuel economy >60mpg by 2025.
  - Batteries 1/2 today's price in 2015, 1/4 today's price in 2020.
  - Fuel cells for vehicles $30/kW; 5000 hour duration.

Battery cost based on 2011 modeled cost of $600/kWh.

Key Alternative Fuels Issues

- Can it Scale-Up ?

    - *For Substantial Contribution to National Energy Supplies*

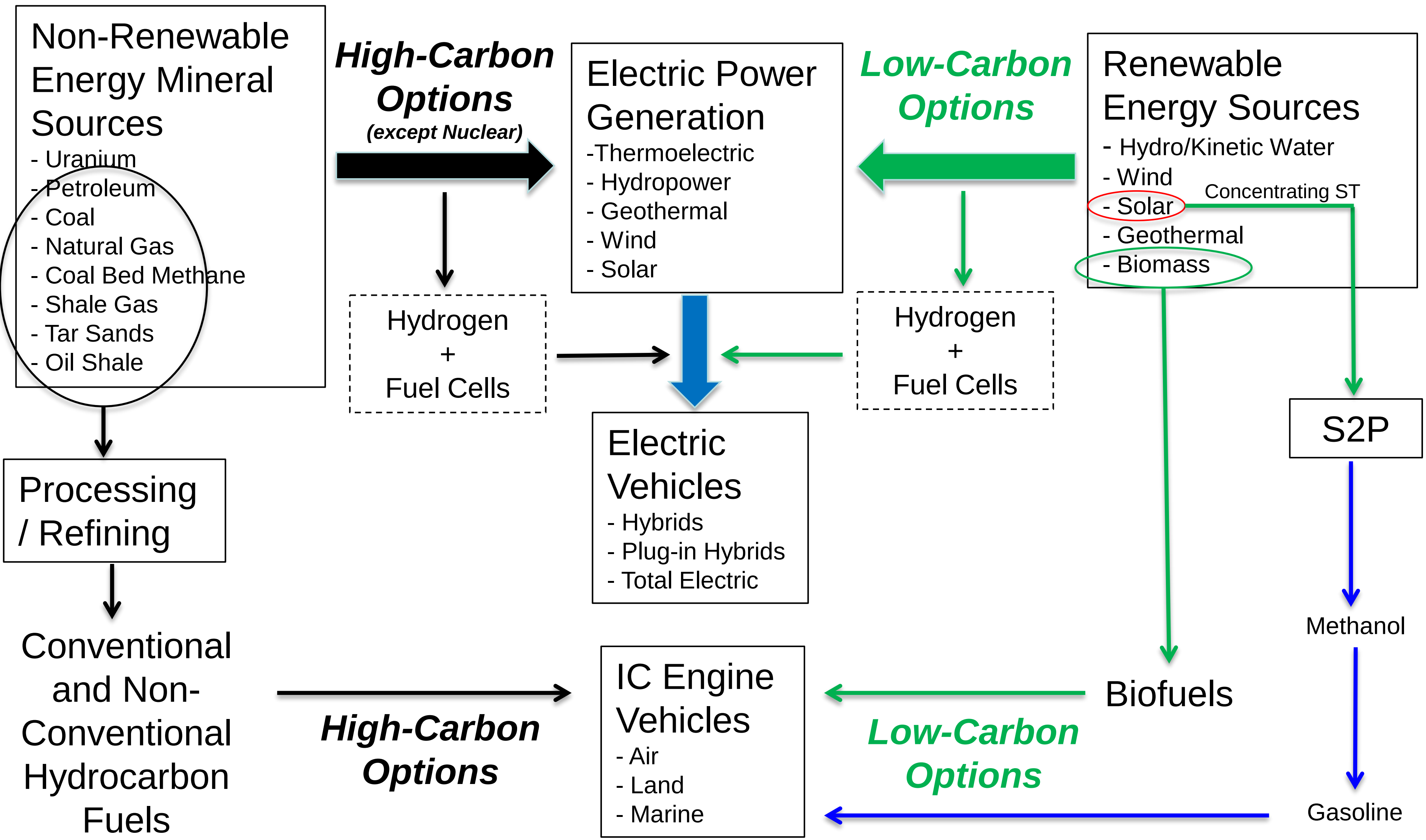
- Can it be Produced “Affordably” ?
- Can it be Produced “Sustainably” ?

    - *With Economic Sustainability*
    - *With Environmental Sustainability*
    - *With Social Sustainability*

- Compatibility with Existing Infrastructure?

The Alternative Fuels Landscape

Focus on Transportation Fuels



DOE/EERE Summary of EV Benefits

http://www.afdc.energy.gov/afdc/pdfs/51017.pdf

What are the Benefits of Electric Drive Vehicles?			
Benefits	**Hybrid Electric Vehicles**	**Plug-In Hybrid Electric Vehicles**	**All-Electric Vehicles**
Fuel Economy	**Better than similar conventional vehicles** The fuel savings of driving a Honda Civic Hybrid versus a conventional Civic is about 38% in the city and 20% on the highway.	**Better than similar HEVs and conventional vehicles** PHEVs use 40% to 60% less petroleum than conventional vehicles and permit driving at slow and high speeds using only electricity.	**No liquid fuels** Fuel economy of EVs is usually expressed as cost per mile, which is discussed below.
Emissions Reductions	**Lower emissions than similar conventional vehicles** HEV emissions vary by vehicle and type of hybrid power system. HEVs are often used to offset fleet emissions to meet local air-quality improvement strategies and federal requirements.	**Lower emissions than HEVs and similar conventional vehicles** PHEV emissions are projected to be lower than HEV emissions, because PHEVs are driven on electricity some of the time. Most categories of emissions are lower for electricity generated from power plants than from vehicles running on gasoline or diesel.	**Zero emissions** EV emissions do not come from the tailpipe, so EVs are considered zero-emission vehicles. However, emissions are produced from the electric power plant. Most categories of emissions are lower for electricity generated from power plants than from vehicles running on gasoline or diesel.
Fuel Cost Savings	**Less expensive to operate than a conventional vehicle** Because of their improved fuel economy, HEVs usually cost \$0.05 to \$0.07 per mile to operate, compared to conventional vehicles, which cost \$0.10 to \$0.15 per mile to operate.	**Less expensive to operate than an HEV or conventional vehicle** When operating on electricity, a PHEV can cost \$0.02 to \$0.04 per mile (based on average U.S. electricity price). When operating on gasoline, the same vehicle can cost \$0.05 to \$0.07 per mile, compared to conventional vehicles, which cost \$0.10 to \$0.15 per mile to operate.	**Less expensive to operate than conventional vehicles** EVs operate using only electricity. A typical electric vehicle costs \$0.02 to \$0.04 per mile for fuel (based on average U.S. electricity price).
Fueling Flexibility	**Same as conventional vehicles**	**Can get fuel at gas stations or charge at home or public charging stations**	**Can charge at home or public charging stations**

Source: Alternative Fuels and Advanced Vehicles Data Center, www.afdc.energy.gov/afdc/vehicles/electric_benefits.html

Challenges to Electric & Hybrid Vehicles

- "Energy density is what counts" (… Tony Tether, former DARPA director):
  - Gasoline delivers about 35 MJ/kg
  - Electric vehicle batteries deliver about 1 MJ/kg
- Relative High Cost and Limited Capacity of Vehicle Battery Technology[1]
  - Rough Rule of Thumb: Battery costs must drop from $600/kwh to $300/kwh to compete against IC engine vehicles burning gasoline at $3.50/gallon
  - Price gap between Electric and IC vehicles must close substantially … via reduced cost of batteries and/or increased cost of hydrocarbon fuels
- Lack of charging infrastructure - Need to install tens of millions of charging stations[1]
- Need to strengthen the utility grid to handle electricity demand by plug-in hybrids[2]
- Need to change utility regulations to promote nighttime recharging
- Where you live (*and how your electric power is generated*) determines how climate-friendly electric vehicles will be … e.g., hydropower vs. coal vs. natural gas.[3]

[1] *Deutch, John and Ernest Moniz, "Electrificaiton of the Transportation System", MIT Energy Initiative Symposium Report, April 8, 2010. http://web.mit.edu/mitei/docs/reports/electrification-transportation-system.pdf*
[2] Hadley, Stanton W. and Alexandra Tsvetkova, "Potential Impacts of Plug-in Hybrid Electric Vehicles on Regional Power Generation", ORLN/TM-2007/150, January 2008. http://www.ornl.gov/info/ornlreview/v41_1_08/regional_phev_analysis.pdf
[3] Anair, Don and Amine Mahmassani, "State of Charge: Electric Vehicles' Global Warming Emissions and Fuel Cost Savings across the United States", Union of Concerned Scientists, Prepublication Verison, April 2012. http://www.ucsusa.org/assets/documents/clean_vehicles/electric-car-global-warming-emissions-report.pdf

Electric & Hybrid Transportation Alternatives

DOE/EERE R&D Investments in Vehicle Technologies Program

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Program Overview

- Suite of technology RD&D includes transportation electrification to lightweight materials, advanced combustion engines, and non-petroleum fuels and lubricant technologies.
- Transportation electrification activities include emerging battery technologies and innovative battery manufacturing processes, power electronics, and electric motors.
- Early demonstration, field validation, and market barrier reduction of advanced technologies and efforts to reduce the vehicle miles traveled by the public.

Budget Request

	Dollars in Thousands	
Activity	FY 2012 Enacted	FY 2013 Request
Innovations	143,978	182,638
Emerging Technologies	113,567	168,209
Systems Integration	19,875	14,043
Market Barriers	43,545	44,237
SBIR/STTR	7,842	10,873
TOTAL	**328,807**	**420,000**

Technology and Focus Areas

- **Battery/Energy Storage** will focus on research in the areas of extremely high energy battery chemistries for use in Electric Vehicles (EVs), Plug-in Hybrid Electric Vehicles (PHEVs), and high power systems for Hybrid Electric Vehicles (HEVs), which offer the promise of significantly lower system costs by reducing the amount of material, processing costs and the number of cells needed. The focus in this area will be new materials and electrode couples that offer a significant improvement in either energy or power.
- **Advanced Combustion Engines** will focus on improving the fuel economy of passenger and commercial vehicles through improvements in engine efficiency. Research on advanced combustion regimes, including homogeneous charge compression ignition (HCCI) and other modes of low-temperature combustion, lean-burn gasoline, and multi-fuel operation, is aimed at achieving this objective.
- **Power Electronics and Electric Motors** will focus on advanced, low-cost technologies and topologies compatible with the high-volume manufacturing of motors, inverters, and DC/DC converters for electric drive vehicles with emphasis on R&D for advanced packaging, enhanced reliability, and improved manufacturability.
- **Materials Research** will focus on enabling the weight reduction of vehicles by addressing fundamental technical barriers and developing new materials such as advanced high strength steels, aluminum, magnesium, carbon fiber, and carbon fiber composites.

Hydrogen Fuel Cell Alternatives

DOE/EERE R&D Investments in Hydrogen & Fuel Cell Technologies

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Program Overview

The Hydrogen and Fuel Cells Technology Program develops technologies to enable fuel cells to be cost-competitive in diverse applications, including light-duty vehicles (at $30/kW) and stationary power (at less than $1,500/kW), and to enable renewable hydrogen (from diverse resources) to be cost-competitive with gasoline ($2 – 4/gge, delivered and dispensed).

Budget Request

	Dollars in Thousands	
Activity	**FY 2012 Enacted**	**FY 2013 Request**
Innovations	64,021	52,441
Emerging Technologies	19,465	15,909
Systems Integration	11,421	6,980
Market Barriers	6,180	2,520
SBIR/STTR	2,537	2,150
TOTAL	**103,624**	**80,000**

Hydrogen and Fuel Cell Technologies leverages other EERE program activities (e.g., Advanced Manufacturing and Vehicle Technologies in key areas such as carbon fiber cost reduction).

Technology and Focus Areas

- **Fuel Cell R&D** will improve the durability, reduce costs, and improve the performance of fuel cell systems, through advances in fuel cell stack materials and components, and in balance of plant components and subsystems. Goal:
  - Reduce costs by increasing PEM fuel cell power output per gram of platinum-group catalyst from 2.8 kW/g (in 2008) to 5.9 kW/g in 2013 and 8.0 kW/g by 2017.
- **Hydrogen Fuel R&D** will focus on production from renewable resources, delivery, and storage R&D to achieve a near-term 10 percent reduction in the delivered, untaxed hydrogen cost from the baseline of $8/gge, and develop hydrogen storage technologies to reduce costs by 10 percent in the near term from $17/kWh.
- **Safety, Codes and Standards** will develop and validate fast-fill models to optimize fueling protocols for SAE J2601.
- **Manufacturing R&D** will develop and demonstrate advanced manufacturing technologies and processes that will reduce the cost of fuel cell systems and hydrogen technologies. Goal:
  - Reduce cost of manufacturing membrane electrode assemblies (MEAs) by 25 percent, relative to 2008 baseline of $63/kW at 1000 units/year by 2013.
- **Systems Analysis** will determine technology gaps, economic potential, infrastructure cost reduction opportunities for early market penetration of fuel cells, crosscutting fuel cell applications and integration for EERE technology portfolio and technology advancement in 2013.

Biomass-Based Fuel Alternatives

DOE/EERE R&D Investments in Biofuel Technologies

Program Overview

The Biomass & Biorefinery Program fund research, development, and demonstration projects to advance biofuels and to validate and assist in the commercialization of integrated biorefinery technologies and the development of biomass conversion technologies. Additionally, the program works to produce a variety of biofuels, bioproducts, biopower and evaluate environmentally sustainable feedstocks.

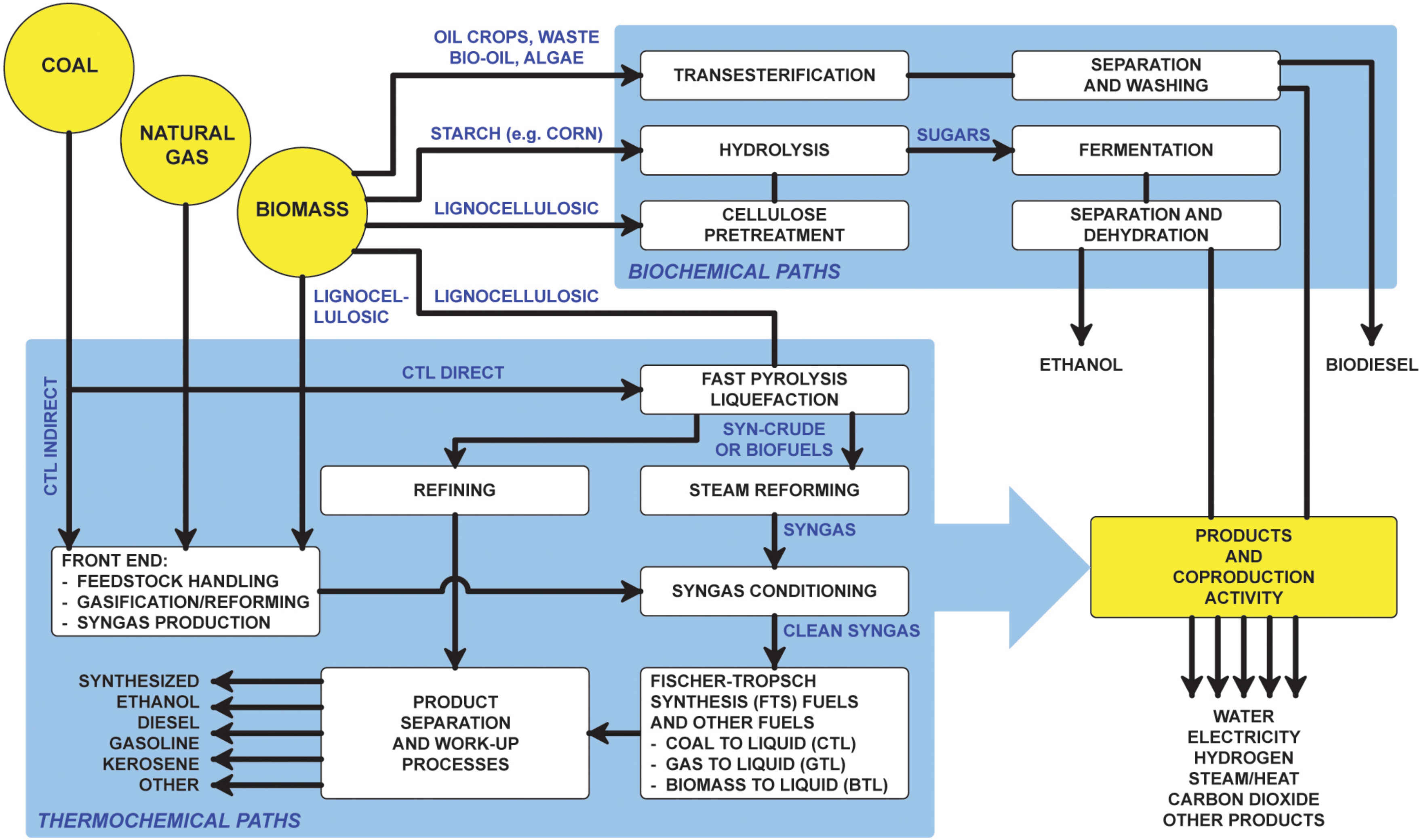
Budget Request

Activity	Dollars in Thousands FY 2012 Enacted	FY 2013 Request
Innovations	89,453	75,344
Emerging Technologies	57,709	84,629
Systems Integration	2,079	62,987
Market Barriers	44,135	42,283
SBIR/STTR	5,900	4,757
TOTAL	**199,276**	**270,000**

Technology and Focus Areas

- **Integrated Biorefineries** activities will continue to support the President's commitment to help entrepreneurs break ground for four next-generation biorefineries – supporting small scale innovative pilots through to larger scale commercial facilities.
- **Biochemical** activities will continue to focus on process integration including pretreatment, clean sugar production and fermentation and/or catalysis to hydrocarbon fuel intermediates and bio-based chemicals. A design case will be developed to target research toward the goal of <$3.00 gal fuel by 2017.
- **Thermochemical** pathway efforts will continue to focus on laboratory scale integration of bio-oil production and upgrading to hydrocarbon fuels. The design cases for fast pyrolysis to biofuels will be re-examined to ensure the optimal cost, carbon and energy-efficient process is chosen.
- **Algae** work include selection of three innovative algae production strains with the necessary traits to produce biofuels, as well as continuation of development of low energy intensity technologies for dewatering algal biomass.
- **Feedstock Logistics** will include the demonstration of using uniform-format densified solid feedstocks and its seamless interface with conversion technology.
- **Biopower** will continue to conduct RD&D on developing more efficient cookstoves with reduced emissions.

Example Fossil and Renewable Feedstocks & Pathways for Liquid Transport Fuel Alternatives



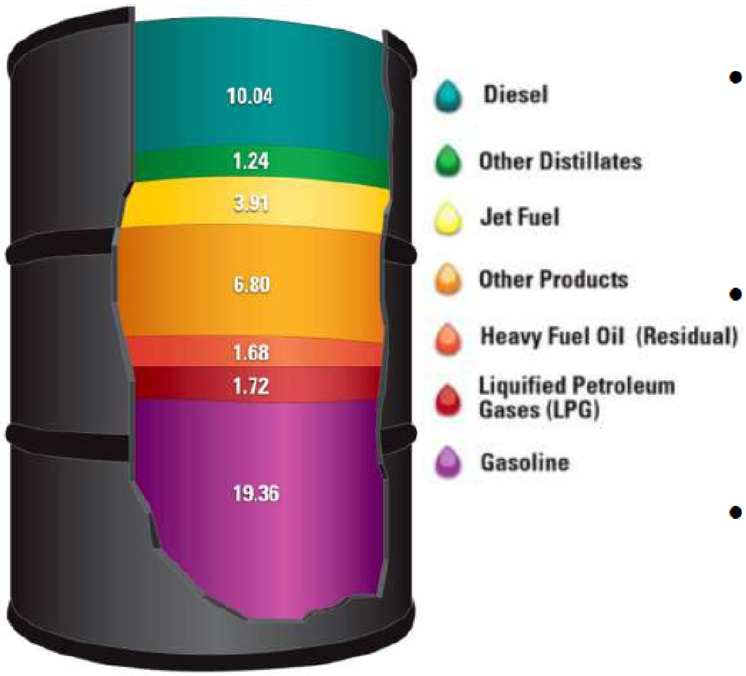
Adapted from: EIA 2006; Huber, et.al., 2006

Alternative Liquid Fuels Challenge:

Replacing the Whole Barrel – Biomass is Low-Carbon Option

Biofuels Trend… toward "infrastructure compatible" drop-in hydrocarbon fuels

Products Made from a Barrel of Crude Oil (Gallons)
(2009)



- U.S. spends more than $1,197M each day on crude oil imports*
- Cellulosic ethanol displaces gasoline fraction only
- Only about 40% of a barrel of crude oil is used to produce light duty petroleum gasoline
- Reducing dependence on oil requires replacing diesel, jet, heavy distillates, and a range of other chemicals and products
- Greater focus needed on RDD&D for a range of technologies to displace the entire barrel of petroleum crude

Source: Energy Information Administration, "Oil: Crude Oil and Petroleum Products Explained" and AEO2009, Updated February 2010, Reference Case.
*American Petroleum Institute.

Comparative Value of Biofuels

Source: DOE/EERE-OBP Quarterly Review, Oct 2011

Lost

Imported crude oil → Cost of production & transport (avg.): $20/bbl + Profit to host country : $55/bbl + Cost of refining & marketing: $30/bbl + Taxes: $20/bbl = Pump price: $125/bbl ($3/gal)

Biomass → Cost of feedstock supply and logistics: $31/bbl + Cost of conversion, distribution, marketing: $74/bbl + Taxes: $20/bbl = Pump price: $125/bbl ($3/gal)

Price differential between imported crude oil and biomass:
$75/bbl x 4.3 x 10^9 barrels/year = $323 billion/year

Sources: EIA, Annual Energy Review
OBP MYPP

Current U.S. Policy-Driver for Biofuels
In Context of Overall US Transportation Fuel Demand

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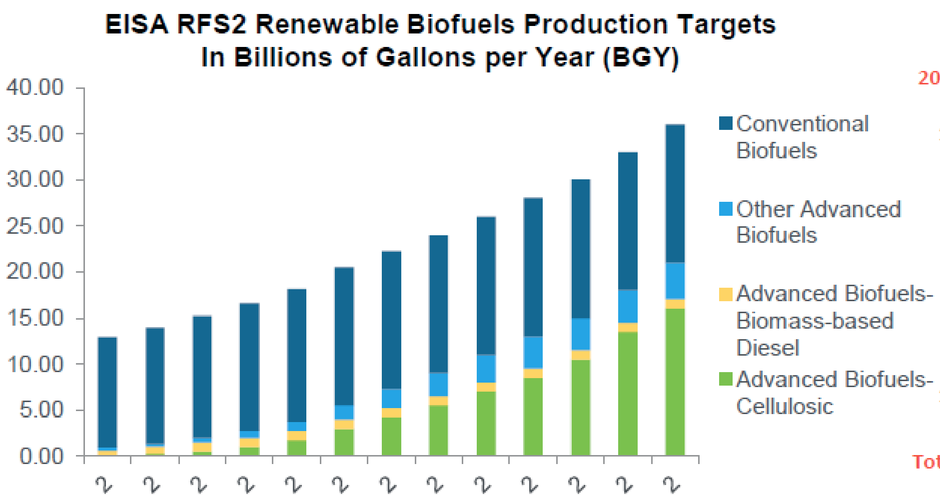
Biofuels Policy Mandate*

* EISA (2007): "Energy Independence and Security Act of 2007", H.R.6, 110th Congress, Public Law No: 110-140 December 19, 2007.



2022 Targets

15 BGY

4 BGY

1 BGY

16 BGY

Total: 36 BGY by 2022

Categories for Algae Contribution

Putting into Context

Fuel Type	2008 Demand**	2020 Projection**	2035 Projection**
Gasoline blend (including E85)	8.99 MBD (137.8 BGY) 17.2 Quads	9.42 MBD (144.4 BGY) 18.1 Quads	10.26 MBD (157.3 BGY) 19.7 Quads
Diesel Fuel	3.94 MBD (60.4 BGY) 8.38 Quads	4.24 MBD (65.0 BGY) 9.02 Quads	4.91 MBD (75.3 BGY) 10.4 Quads
Jet Fuel	1.54 MBD (23.6 BGY) 3.19 Quads	1.68 MBD (25.8 BGY) 3.48 Quads	1.84 MBD (28.2 BGY) 3.81 Quads

U.S. Fuel Demand**

** "Annual Energy Outlook 2010: with projections to 2035" U.S. Energy Information Administration Department of Energy DOE/EIA-0383 (2010).

Not All Fuels are Alike

Energy Density Differences and Infrastructure Compatibility

(yellow box) - Denotes fuels fully compatible with current infrastructure[1]

Ethanol[2]	Gasoline[2]	Biodiesel[2]	Diesel Fuel[2]	Jet Fuel[2]
~84,600 Btu/gal	*~125,000 Btu/gal*	*~126,200 Btu/gal*	*~138,700 Btu/gal*	*~135,000 Btu/gal*
Energy Density (Volumetric) Relative to Conventional Gasoline				
~0.68	*1.00*	*~1.01*	*~1.11*	*~1.08*
Fuel Volume per Quad of Energy Content in Billions of Gallons per Quad (Bgal/Quad)[3]				
~11.8	*~8.00*	*~7.92*	*~7.21*	*~7.41*

[1] Hydrocarbon fuels transport, storage, distribution, and end use (e.g., engines and vehicles)

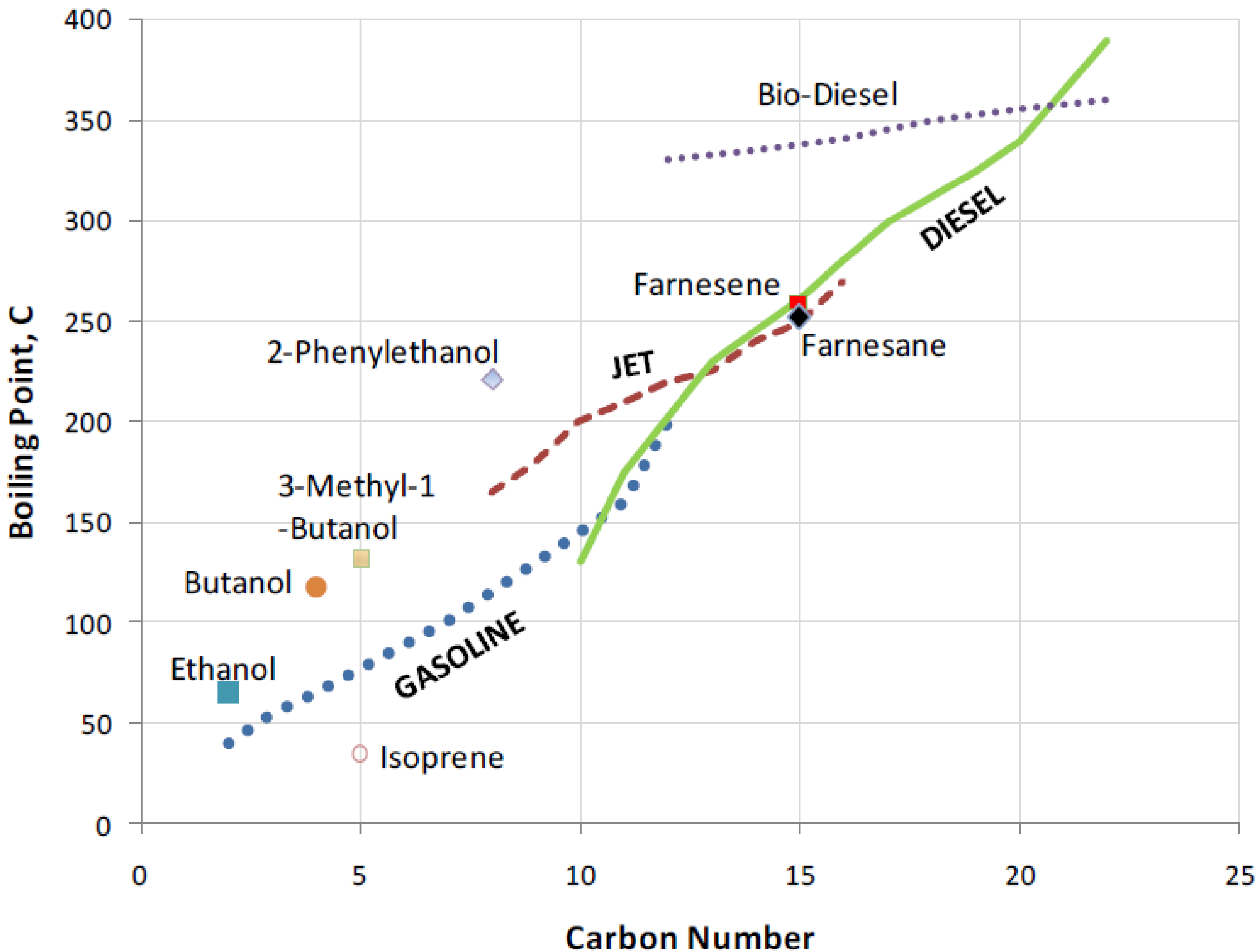
[2] Higher heating values for the various fuels are taken from:

Davis, et al. (2010). Stacy C. Davis, Susan W. Diegel, and Robert G. Boundy, "Transportation Energy Data Book: Edition 29", ORNL-6985, Oak Ridge National Laboratory, DOE/EERE Vehicles Technology Program, July 2010. http://cta.ornl.gov/data/download29.shtml

[3] Quad = 1-Quadrillion Btu's = 10^{15} Btu, where 1-Btu = 1.055 kJ = 2.93×10^{-4} kWh

Hydrocarbon Fuel Blendstock Requirements

- *Existing hydrocarbon fuels span a large boiling point range*
- *Many biofuels pathways make single molecule fuels*
- *Single molecule biofuels have limited blend allowance*



Biomass-Based Fuels … Chemical Flexibility

Numerous Pathways Identified and Being Pursued

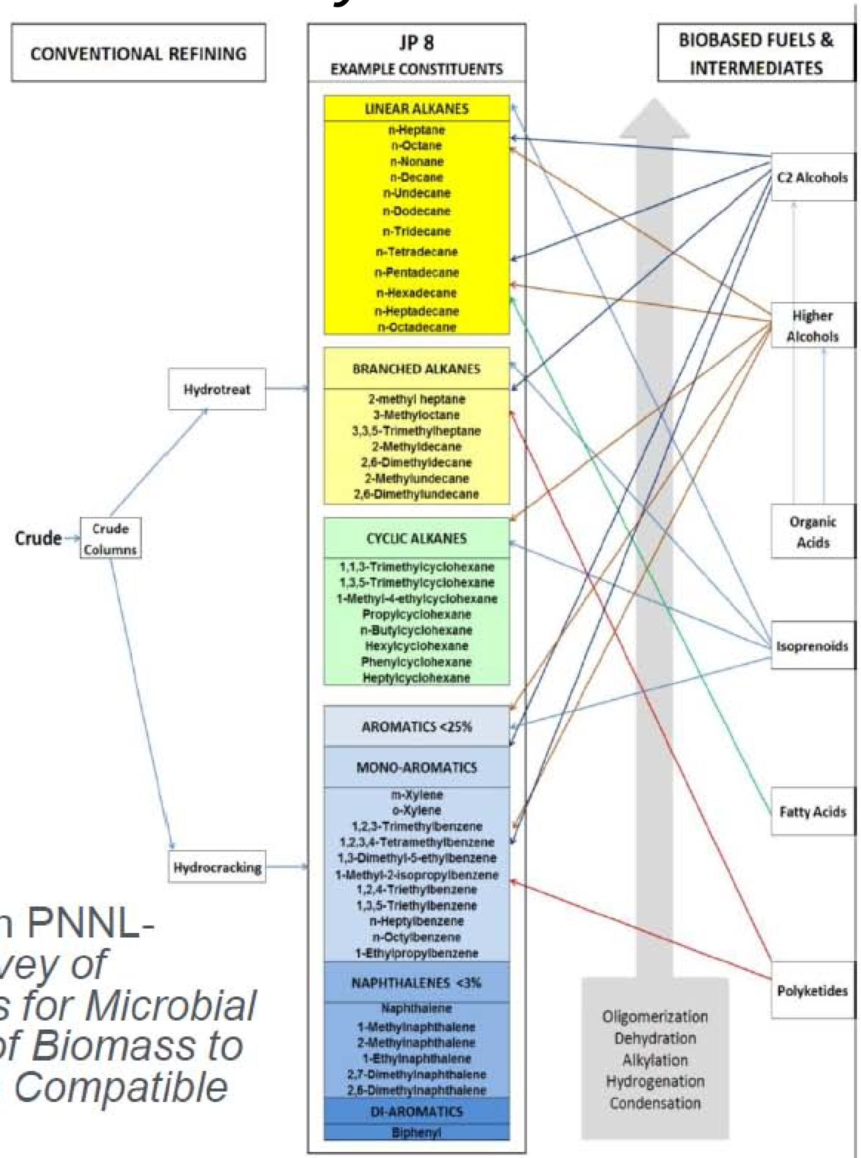


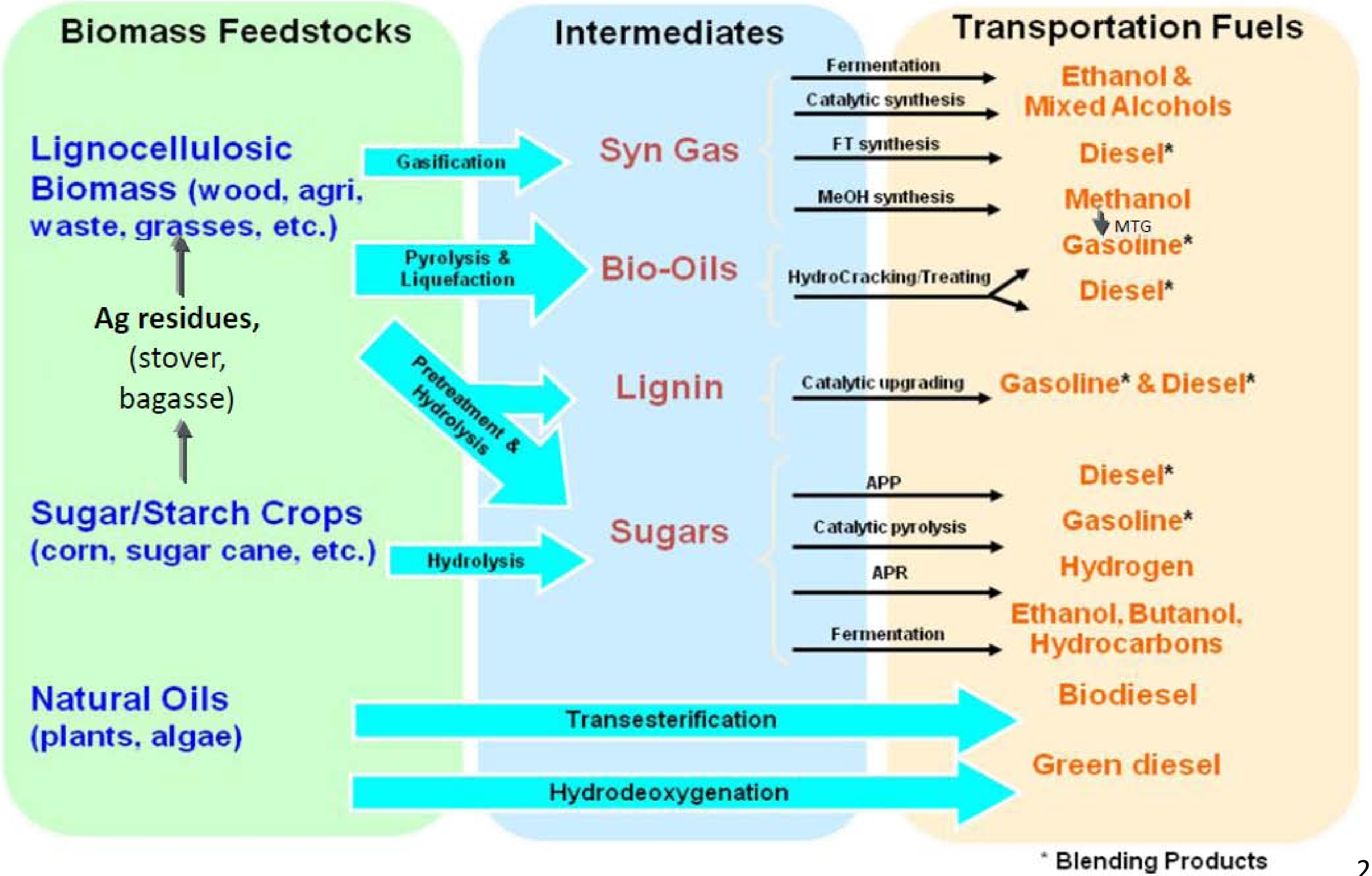
Diagram from PNNL-19704 *A Survey of Opportunities for Microbial Conversion of Biomass to Hydrocarbon Compatible Fuels*

- 19 bio-based fuels & intermediates pathways
- 5 chemistries

…for JP8

- JP8 is a blend of many components.
- Refineries have limited ability to shift between fuels (gasoline, diesel, jet).
- Biochemical processing may also involve multiple steps, but can be tailored to make desired molecules without quantity restrictions.

Biomass-Based Transportation Fuel Options



Advanced Biofuels from Cellulosic Biomass

Big Potential, but Involves Complex Systems 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.

Advanced Biofuels from Cellulosic Biomass

Big Potential, but Involves Complex Systems Problems

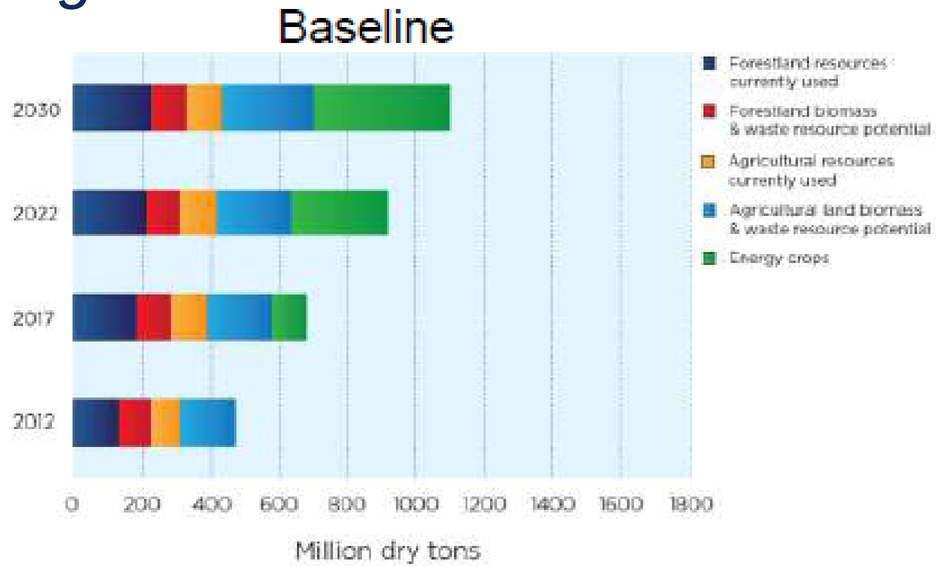
- Although crystalline cellulose is chemical homogeneous, no single enzyme is able to hydrolyze it, whereas soluble cellulose derivatives are easily degraded by a single endo-ß-1,4-glucanase.
- Enzyme mechanisms generally depend on single molecules fitting in their substrate pocket - with cellulose the 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).

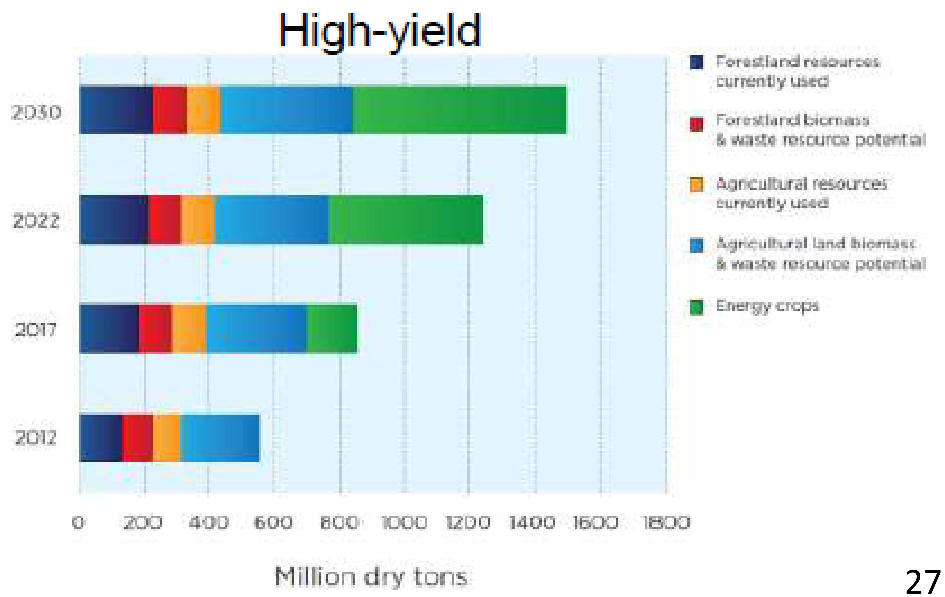
Lignocellulosic Biomass Resource Assessment

Billion Ton Study Update Findings for U.S.

- **Baseline scenario at $60/dry ton**
  - **2012**
    - **About 473 million dry tons annually**
    - **45% is currently used for energy**
  - **2030**
    - **Nearly 1.1 billion dry tons annually**
    - **About 30% as used**
    - **70% as potentially additional**

- **High-yield scenario at $60/dry ton**
  - **Total resources**
    - **Ranges from nearly 1.4 to over 1.6 billion dry tons annually (1% to 4% yield increases)**
    - **80% is potentially additional**
  - **No high-yield scenario for forest residues**





Biochemical Strategies and Technologies

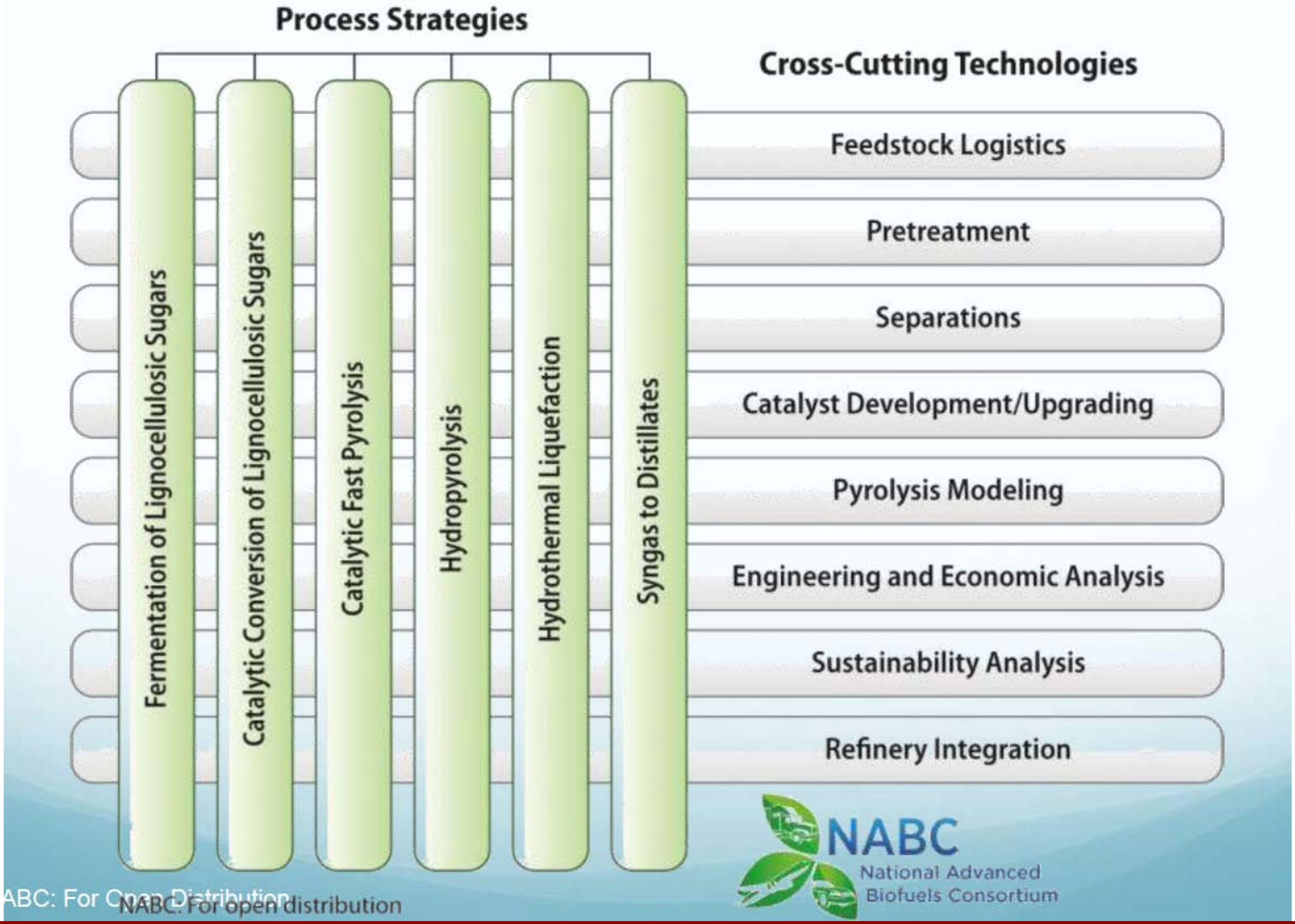
The Joint Bio-Energy Institute – DOE Office of Science

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

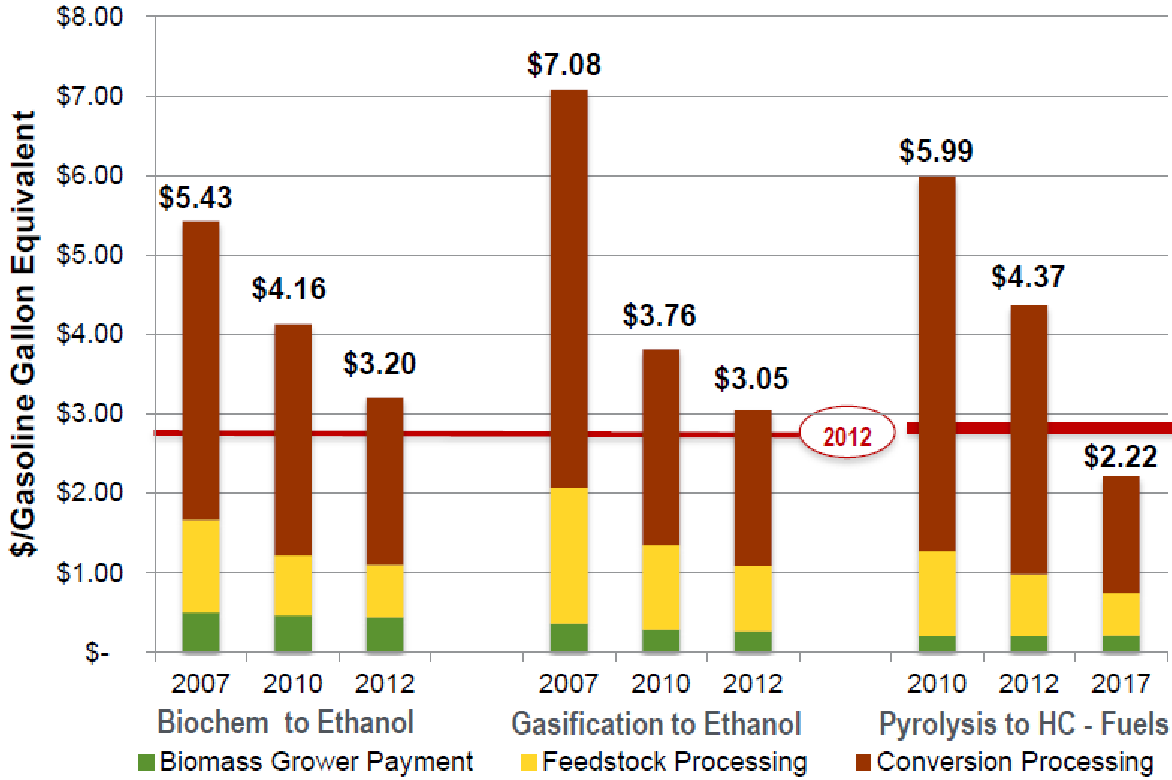
Mixed Bio/Thermo Strategies and Technologies

e.g., National Advanced Biofuels Consortium – DOE/EERE



Advanced Biofuel Production Cost Profiles

DOE/EERE Baseline Trends, Projections, and Target Goals



2012:
$1.76/gallon of ethanol ($2.62/GGE)

2017:
$2.85/gallon of renewable gasoline
$2.84/gallon of renewable diesel
$2.76/gallon of renewable jet
(costs in 2007 dollars).

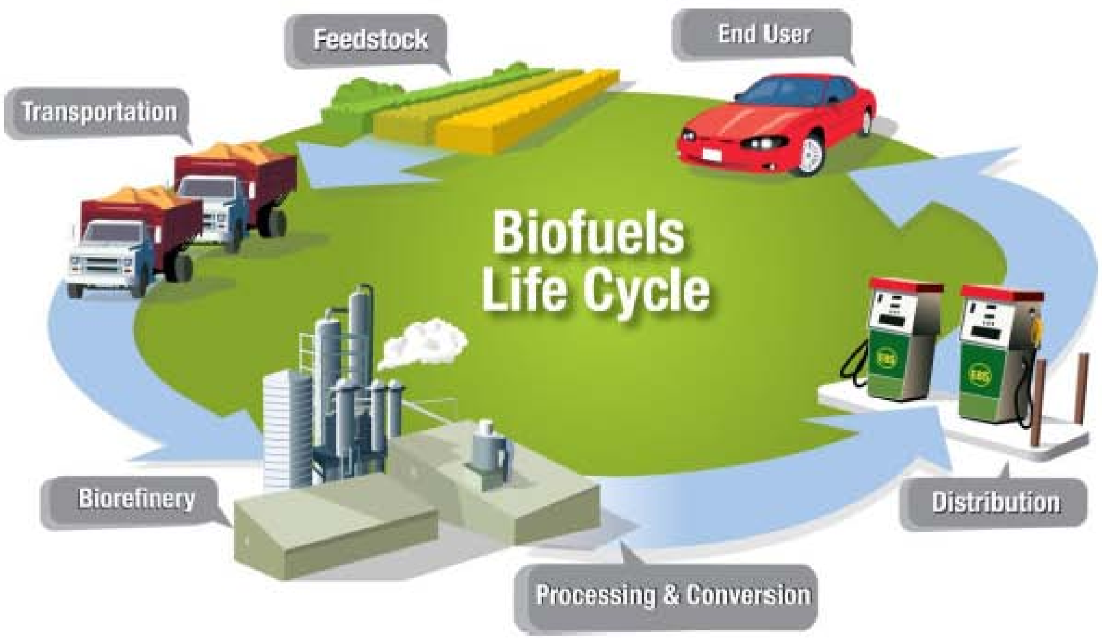
- Focus on RD&D of cellulosic biofuel technologies to help reduce the cost of production and spur private sector investment in biorefineries
- Cost of production of cellulosic biofuels – currently higher than conventional petroleum (and starch-based) fuels
- Production costs going down substantially as a result of Program support, declines projected to continue
- Biochemical drop in fuels – under study

Biofuels Cross-Cutting Systems Issues
Systems Analysis and Associated Technology R&D

Sandia Analysis Capabilities Include GIS, System Dynamics Modeling, Interdependencies Assessments
Sandia Technology R&D Capabilities Include Biology, Biochemical and Thermochemical Processes, Separations Technologies, Systems Integrations, and Diagnostics

State-of-technology techno-economic assessments

Land-use change model development



GIS-based assessment of optimal feedstock resource potential

Well-to-wheels analysis and expansion of GHG Emissions and Energy Use in Transportation (GREET) model for emerging biofuels production pathways

Biofuels Sustainability

Involves complex energy-water-land-resource system interdependencies

Feedstock production and logistics

- Evaluate nutrient and carbon cycling
- Assess impact on land and resource use

Conversion

- Minimize water consumption, air pollution, and carbon footprint
- Utilize co-products and fully integrate systems
- Maximize efficiency

ethanol

diesel

gasoline

jet fuel

biopower

bioproducts

End use

- Minimize GHG emissions
- Avoid negative impacts on human health

Cross-cutting

- Life-cycle analysis of water consumption and GHG emissions
- Land-use change modeling
- Water quality analysis
- Environmental, economic, and social factors

Current DOE Biofuels Program Efforts

Analysis and Sustainability … multiple labs involved

Ongoing Work:

- Peer Reviewed techno-economic analyses
- WTW GHG Emission Modeling
- GIS based Resource Assessments

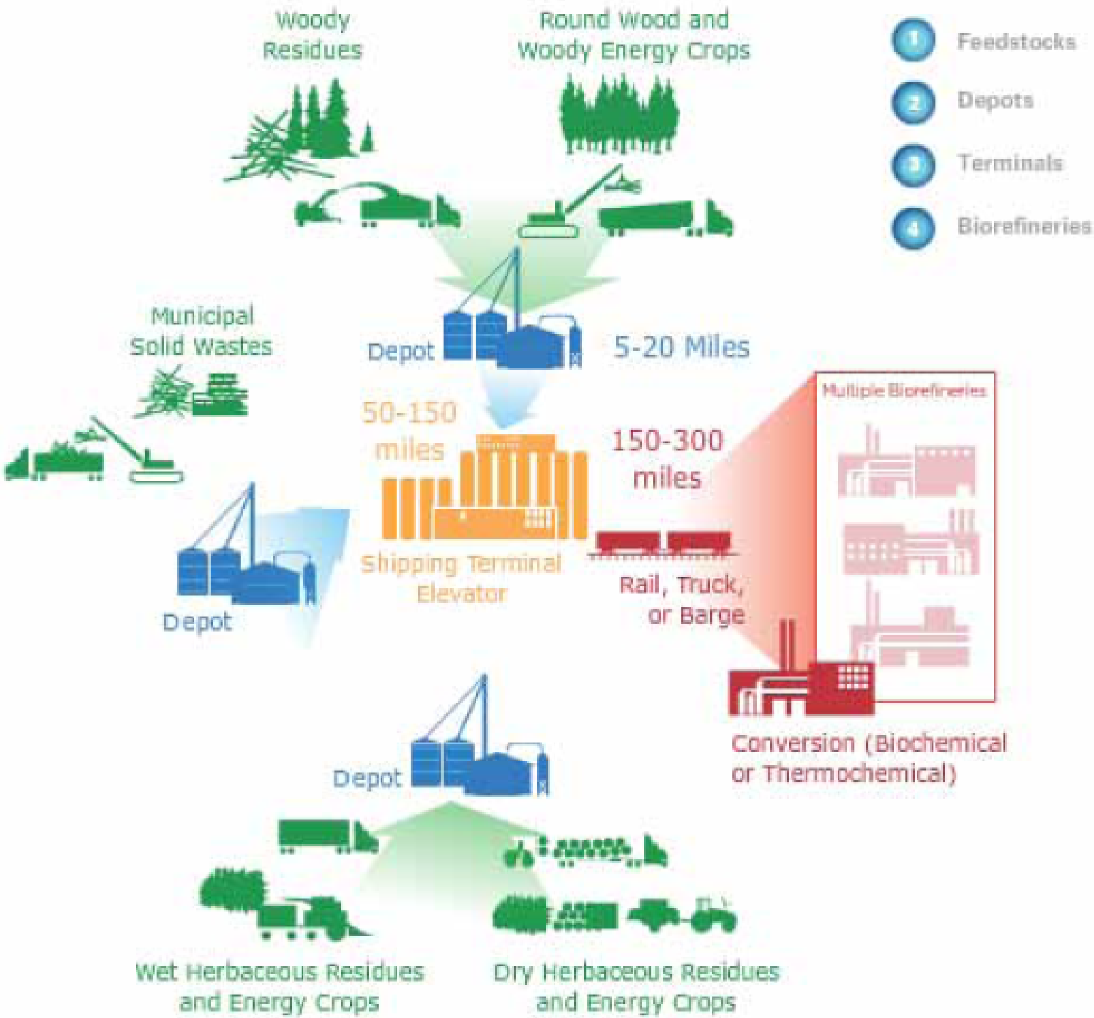
Barriers:

- Availability of High Quality, Public Data
- Still "Developing" Process Strategies
  - *many potential pathways/intermediates to hydrocarbon fuels/products*
  - *some ill-defined unit operations relative to cellulosic ethanol*
  - *New separation/product recovery strategies and lignin utilization strategies needed*
- Lack of Consistent Analytical Approach
  - *assumptions drive recommendations*

Critical R&D Activities:

- High level Hydrocarbon Fuel Scoping Study
  - *compare a variety of bio-oil and sugar intermediate routes to HC fuels; identify baselines and/or gaps in experimental information, guide R&D opportunities*
- Refinery Integration and Co-location Study
  - *evaluate economic impact of refinery integration, perform comprehensive TEA to guide selection of feasible intermediates, examine trade-offs between economy of scale advantages in refinery and transportation*
- Lignin Utilization Study
  - *evaluate fuel and value added product options that could be generated from lignin or lignin monomers/oligomers*

Current DOE Biofuels Program Efforts
Feedstock Logistics … multiple labs involved



Existing Supply Systems	Depot Supply Systems
Nearer-term Platform Focus (through 2012)	Longer-term Platform Focus (2013+)
Access to a niche or limited feedstock resource	Access to a broader resource
Based on a dry supply system design (field-dried feedstocks)	Allows higher-moisture feedstocks into supply system
Designed for a specific feedstock type (dry corn stover)	Design addresses multiple feedstock types

Current DOE Biofuels Program Efforts
Feedstock Logistics … multiple labs involved

Ongoing Work:
- Billion Ton Study Update
- Sun Grant Initiative
- Uniform Format Feedstock Approach

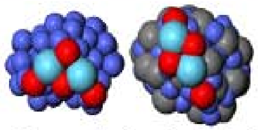
Barriers:
- Low Energy Density
  - *Current model is small, decentralized plants*
  - *Difficulty maximizing economies of scale*
- Compositional Reliability/Variability
  - *Inter-crop, inter-variety, seasonal,*
  - *Geographical, storage effects, etc.*
  - *Moisture, ash, sugar content, etc.*
- High Relative Cost
  - *Largest cost contributor to biofuels production*
- Impact of Harvesting/Storage on
- Downstream Conversion
  - *Densification and product uniformity strategies*

Critical R&D Activities:
- Explore densification strategies to lower feedstock cost
- Define specifications at Feedstock/Conversion Interface
- Develop genetically modified feedstocks with higher sugar composition and lower recalcitrance
- Develop harvesting, collection and storage methods that minimize contamination and sugar degradation
- Determine impact of harvesting/logistics strategies on downstream conversion
- Understand and optimize the sustainability aspects of feedstock harvesting, logistics and storage operations

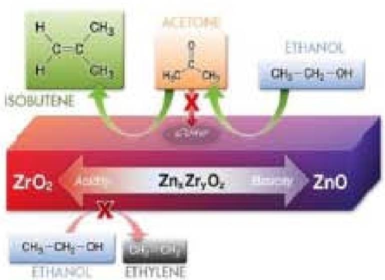
Current DOE Biofuels Program Efforts
Catalysis … multiple labs involved

Chemical Catalysis

Fundamental Science | **Applied R&D** | **Integration and Demonstration**

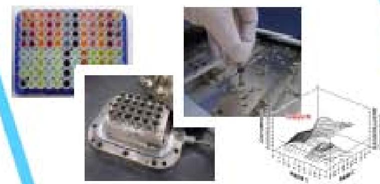


Computation is helping to shape our understanding of metal-metal and metal-support interactions in catalytic materials.



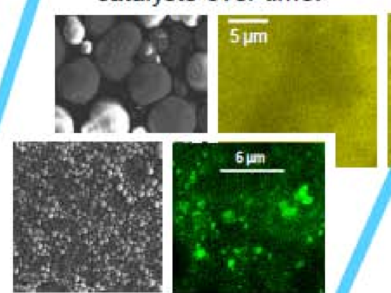
The design of new catalytic materials with precise active sites for selective deoxygenation.

Developing robust catalysts for biomass-derived process streams



Tools available are accelerating catalyst discovery and testing.

Surface science tools are providing details on changes to catalysts over time.



Validating and piloting

Catalysts are validated through thousands of hours of operation in continuous reactors. Integrated process can be demonstrated.

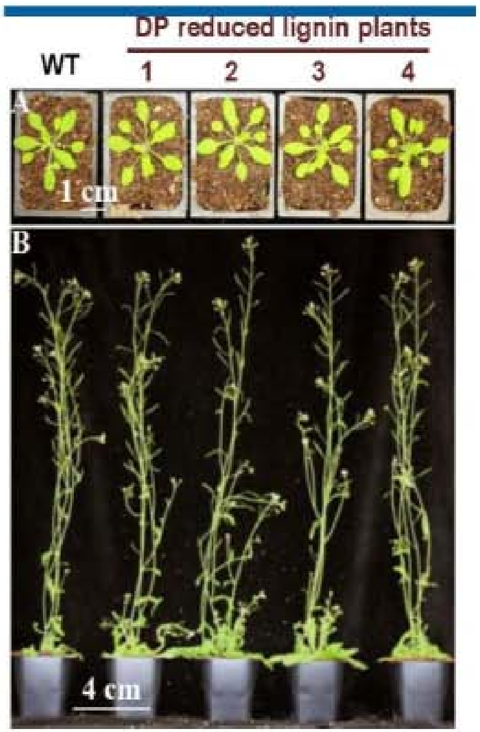
Current DOE Biofuels Program Efforts

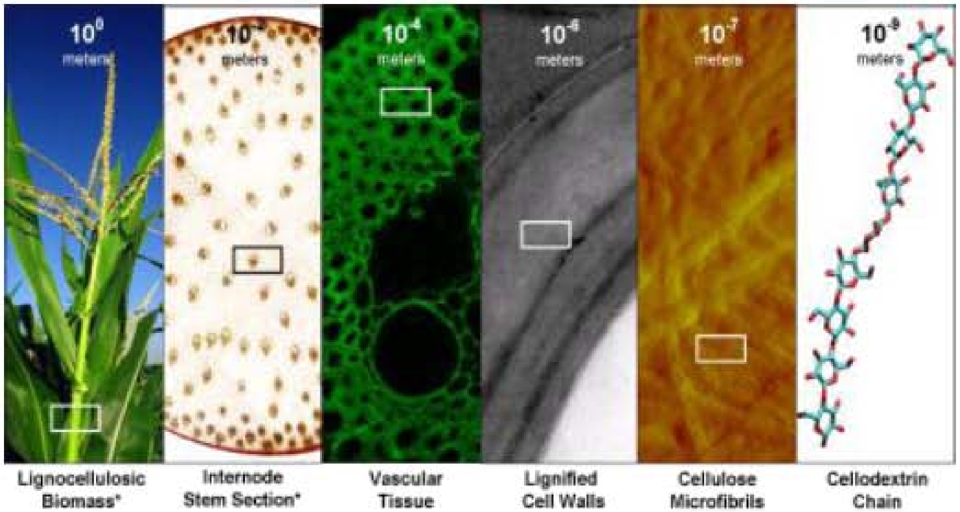
Catalysis … multiple labs involved

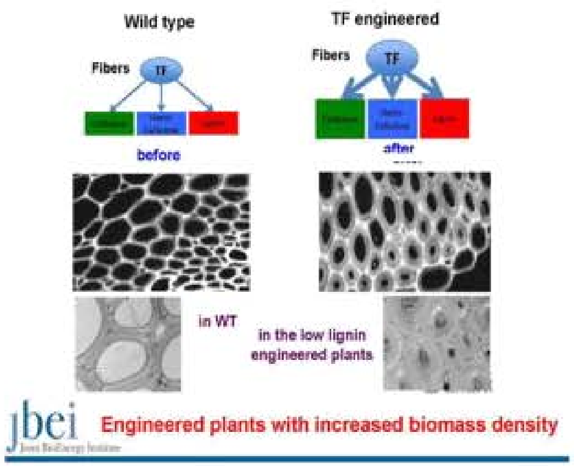
Sandia National Laboratories

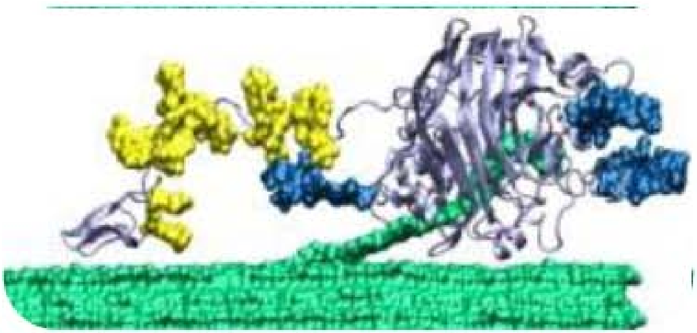
Biotechnology and Biocatalysis

Research provides insight into the cell wall. The insight is used to develop new plant species, improved enzymes for deconstruction, and advanced organisms for converting sugars/carbohydrates into organic acids, alcohols, and hydrocarbons.









Current DOE Biofuels Program Efforts

Catalysis … multiple labs involved

Ongoing Work:

- **Catalyst Design, Characterization and Testing**
- **Enzyme/Organism Characterization and Development**
- **Biomass/Catalyst Surface Characterization**

Barriers:

- **Poor Selectivity Towards Desired Reactions**
  - *Decreases process/carbon efficiency*
  - *Increases coke formation/volatiles formation/catalyst deactivation*
  - *Low sugar utilization in fermentation*
- **Poor Understanding of Rxn Fundamentals**
  - *Kinetics, mechanisms, competing reactions, surface interactions in complex mixtures*
- **Limited Catalyst Lifetime Data**
  - *Catalyst deactivation and organism/enzyme inhibition an issue*
  - *Catalyst stability and regenerability*

Critical R&D Activities:

- **Enhance selectivity towards desired reactions**
  - *Better understanding of catalyst-biomass surface interactions through modeling, spectroscopy, and empirical relationships*
- **Investigate novel processes and catalysts**
  - *H_2 addition during pyrolysis, hydrogen*
  - *Donor/shuttle molecules, consolidated*
  - *Bioprocessing, thermo-tolerant enzymes,*
  - *Genetically improved organisms*
- **Improve catalyst lifetimes**
  - *Develop more robust catalysts and inhibitor tolerant organisms*
  - *Improve aqueous phase catalysts (stability and selectivity) in presence of hydrolyzates*
- **Industrially Relevant Long Term Testing**

Current DOE Biofuels Program Efforts
Separations … … multiple labs involved

Sandia National Laboratories

Ongoing Work:

- **Inhibitor Mitigation/Removal from Slurries**
  - *De-acetylation*
- **Gas/Liquid Filtration of Pyrolysis Vapors/Oils**

Barriers:

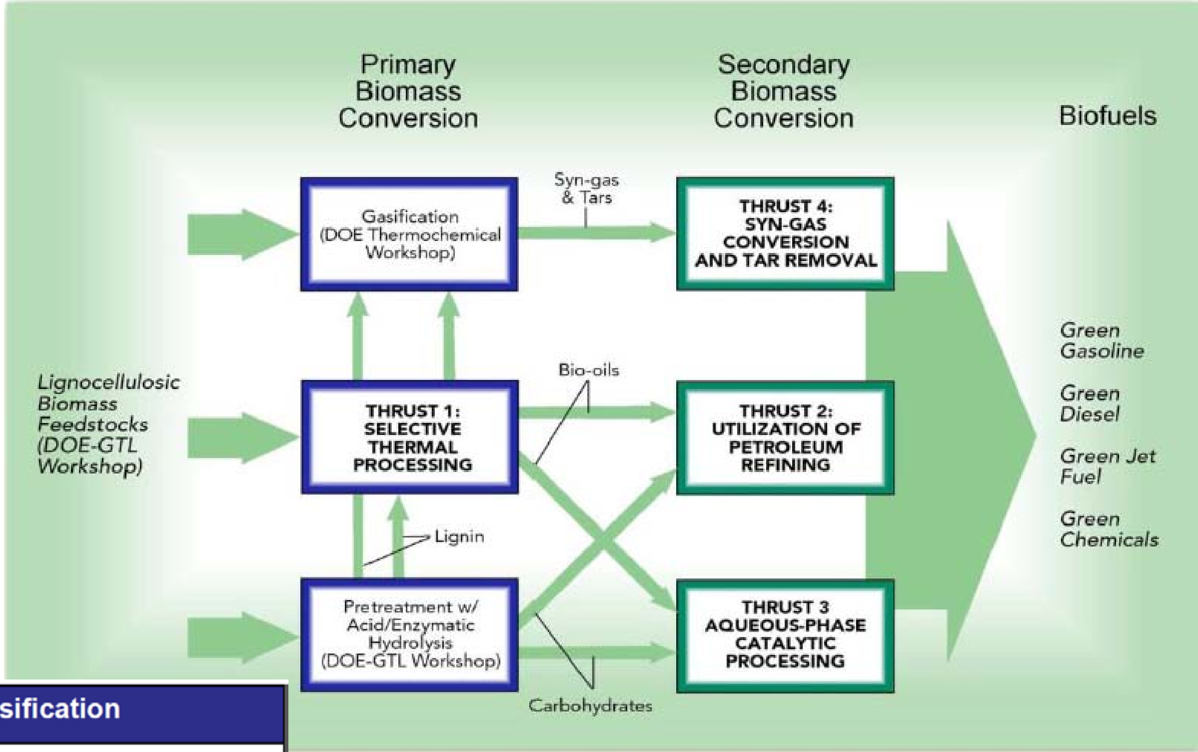
- **Product Recovery for HCs Different than EtOH**
  - *Potentially less energy intensive but more complex than fractional distillation*
- **Poor Understanding of Purification Needs**
  - *Emerging organisms/catalysts will have own set of tolerances to inhibitors/contaminants*
  - *Extensive concentration of intermediates?*
  - *Solid/liq. separation in intermediates/products*
- **Economic Routes to Reagent Recycling and Product Recovery**
- **Membrane/Filter Durability for Biofuels**

Critical R&D Activities:

- **Explore Feasibility of Current Technology to Biomass Applications**
- **Identification and Mitigation of Key Inhibitors/Contaminants**
- **Development of Novel Separation Techniques/Materials**
- **Integrate Separations and Conversion**
  - *Product removal during fermentation*
  - *Catalysis during filtration*
  - *Reactive distillation*
- **Explore Reagent Recycling Strategies**
- **Industrially Relevant Long Term Testing**

Current DOE Biofuels Program Efforts

Thermo-Chem Processing of Lignocellulosic Biomass

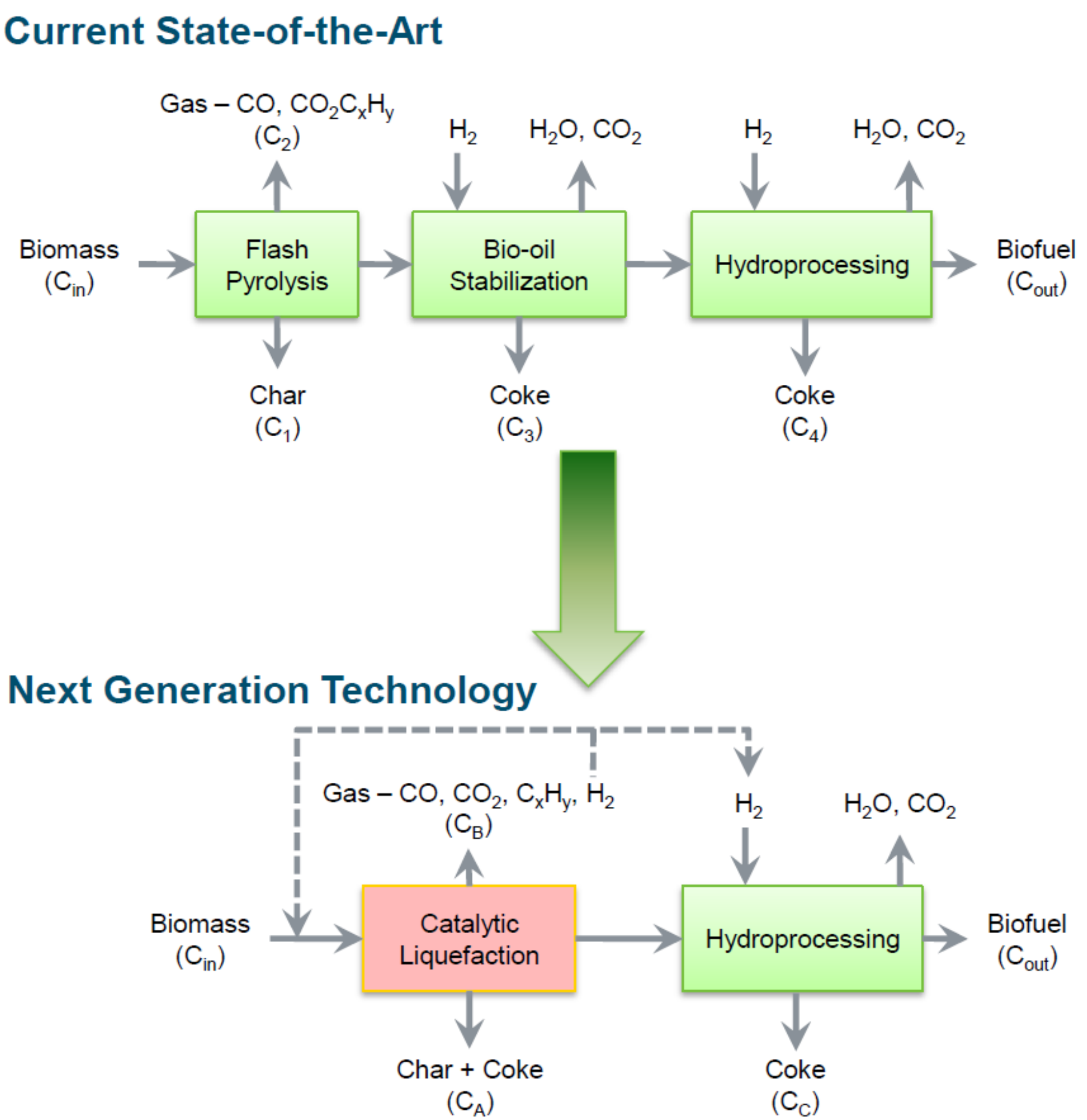


Key Process Challenges

Pyrolysis	Liquefaction	Gasification
Stability	High viscosity	Feedstock processing
Acidity	Elevated oxygen content	Tar Reduction
High oxygen content	Pressure	Fuel Synthesis
Upgrading required for use as fuel	Upgrading required for use as fuel	Catalyst Discovery & Development
Chemical complexity	Chemical complexity	

Current DOE Biofuels Program Efforts

Bio Oil Production… multiple labs involved



Bio-oil Production Technology Options

- **Fast Pyrolysis**
  (0.1 MPa and ~500° C)
- **Bio-oil Stabilization**
  (10 MPa, 150-250° C)
- **Hydroprocessing**
  (20 MPa, 300-350° C)

- **Catalytic Fast Pyrolysis**
  (0.1 MPa and ~500° C)
- **Hydrothermal Liquefaction**
  (~20 MPa and ~375° C)
- **Hydropyrolysis**
  (1-5 MPa (H_2) and ~ 375° C)

Current DOE Biofuels Program Efforts

Bio Oil Production… multiple labs involved

Key Technical Barriers

•Limited understanding of chemical and catalytic mechanisms and kinetics pertaining to the thermal depolymerization of biomass.
•How can we optimize process conditions and catalyst performance to maximize bio-oil yield and quality while reducing the impact of feedstock variability and impurities?

•Limited understanding of the impact of the physical and chemical properties of bio-oil on downstream upgrading processes.
•How can the thermal stability of bio-oil be improved and impurities be removed to facilitate economical upgrading to biofuels?

•Petroleum refining processes are not optimized for hydrocarbon liquids with high oxygen content, like bio-oils.
•How can carbon efficiency be maximized during bio-oil deoxygenation?

•The physical and chemical properties of bio-oil are not compatible with existing refinery infrastructure.
•How can acidic bio-oils with high moisture content be integrated into existing petroleum refineries without severely impacting boiling point distributions and materials of construction?

Critical R&D Activities

•Fundamental studies for understanding reactions, mechanisms, and kinetics of vaporization, catalytic deoxygenation, and bio-oil stability
•Develop thermal stability and quality metrics for bio-oil
•Identify and minimize bio-oil impurities (ash elements, chlorides, water) that reduce the performance of downstream upgrading catalysts
•Determine oxygen functionality and impurities that reduce bio-oil stability.
•Develop improved, multi-functional heterogeneous catalysts to:
•Balance hydrodeoxygenation, decarboxylation, and decarbonylation pathways for minimizing oxygenate and water production
•Maximize carbon efficiency during bio-oil production
•Develop & demonstrate (1000 hrs) novel integrated bio-oil production processes that:
•Maximize carbon conversion to bio-oil
•Reduce process complexity
•Maximize thermal integration
•Minimize or eliminate external H2 consumption thus reducing both capital and operating costs

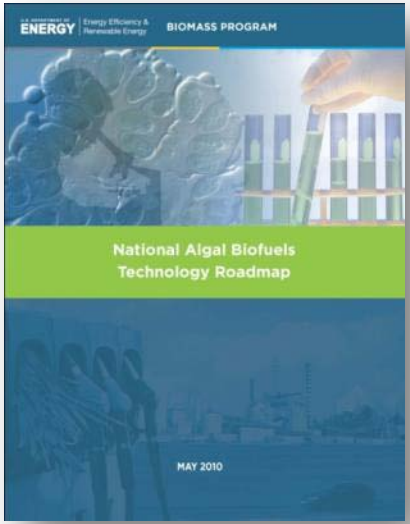
Algae Biofuels
Benefits and Challenges

Benefits of Algal Biofuels

- High productivity potential
- Minimizes competition with agriculture
- Can use waste and salt water
- Recycles carbon dioxide and other nutrients (N, P, etc.)
- Integrated production of fuels and co-products

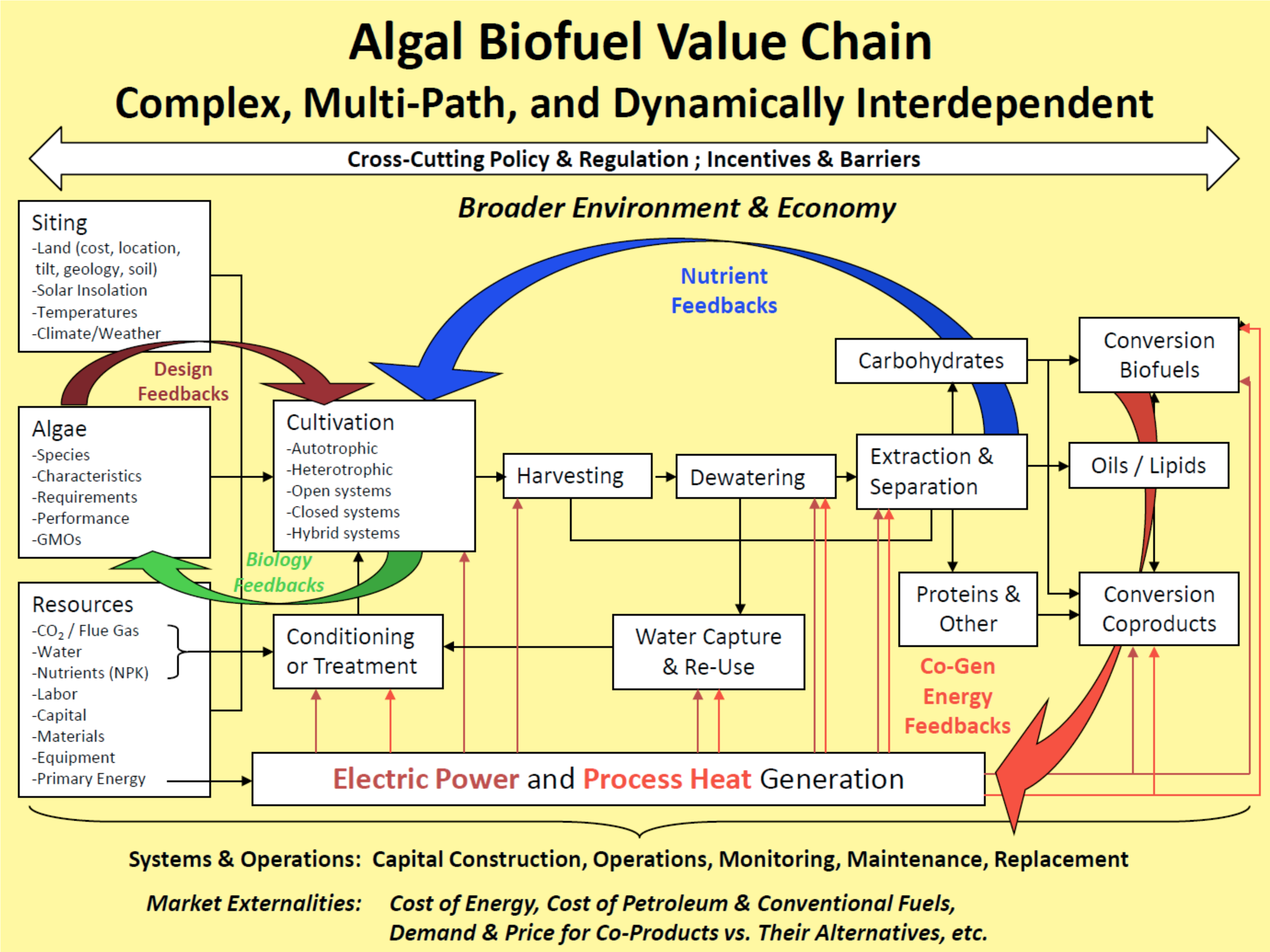
Challenges to commercializing Algal Biofuels

- Affordable, scalable, and reliable algal biomass production
  - Reliable feedstock production & crop protection at scale
  - Energy efficient harvesting and dewatering
  - Extraction, conversion, and product purification
  - Siting and sustainability of resources
- Algae Biofuels Technology Roadmap, released June 2010, helps guide RD&D http://www1.eere.energy.gov/biomass/pdfs/algal_biofuels_roadmap.pdf

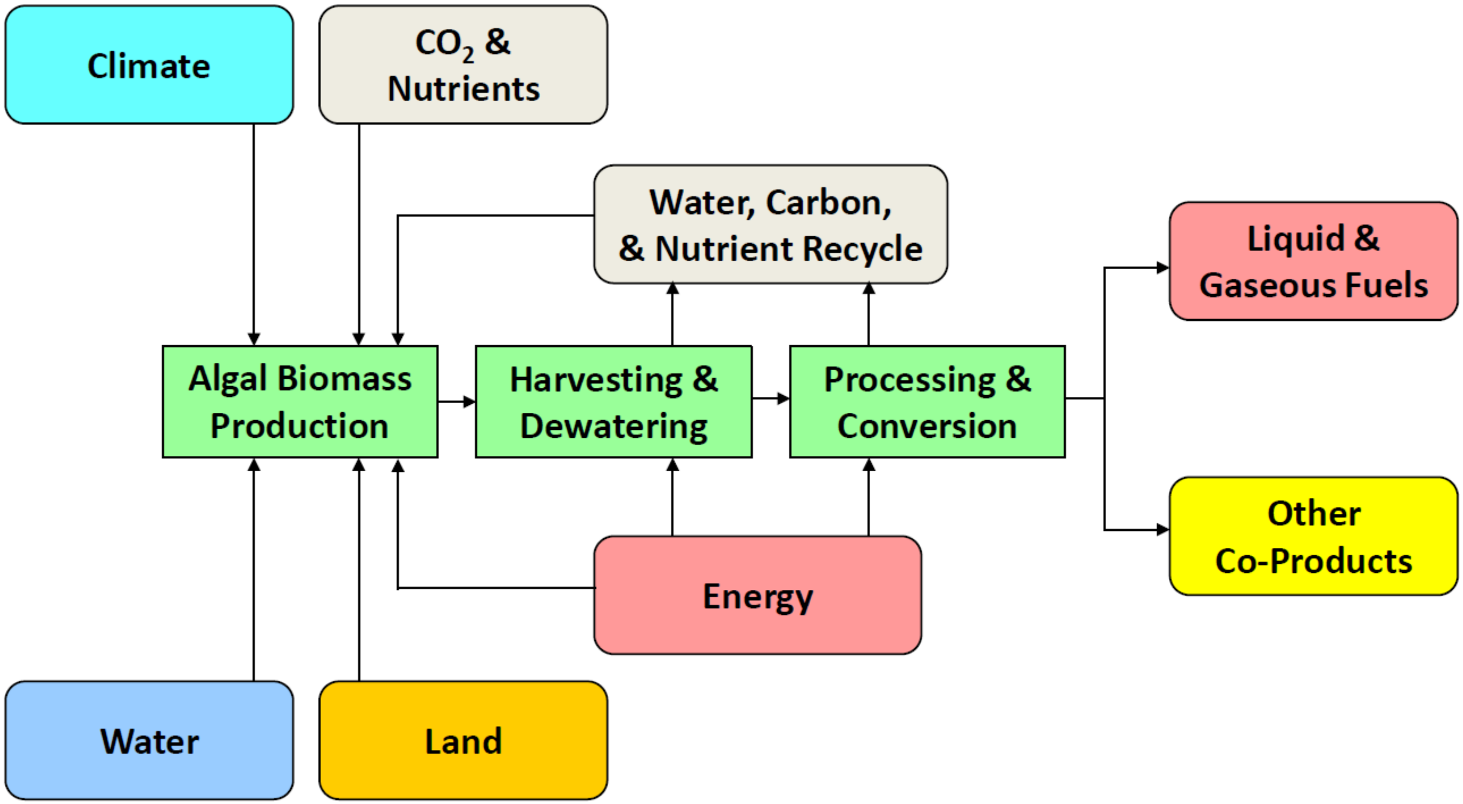


Algae Biofuels Production

Example of a Complex Systems Analysis Challenge



Simplified Algae Biofuels Production Process



Resources and Environmental Parameters

Climate
Solar Insolation
Temperature
Evaporation
Precipitation
Weather Events

Water
Surface/Ground
Location/Access
Supply/Allocation
Salinity/Chemistry
Sustainability

Nutrients
CO2, Organic Carbon
N, P, Other
Sources/Supplies
Cost & Availability
Sustainability

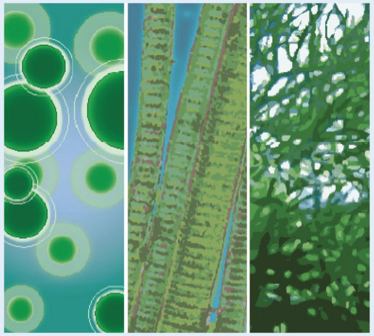
Land
Location/Use Category
Topography
Soil type/Ground Cover
Geology/Hydrology
Ownership/Access

Energy
Electric Power
Process Heat
Fuel Resource Use
Life Cycle Emissions
Cost & Availability

Key Algae Biofuels Process Steps

Source: DOE Algae Biofuels Technology Roadmap

ALGAE FEEDSTOCKS



MICROALGAE CYANOBACTERIA MACROALGAE

Algae as feedstocks for bioenergy refers to a diverse group of organisms that include microalgae, macroalgae (seaweed), and cyanobacteria (formerly called “blue-green algae”). Algae occur in a variety of natural aqueous habitats ranging from freshwater, brackish waters, marine, and hyper-saline environments to soil and in symbiotic associations with other organisms.

Understanding, managing, and taking advantage of the biology of algal strains selected for use in production systems is the foundation for the processing of feedstocks into fuels and products. Isolating new strains directly from unique environments will ensure versatile and robust strains for mass culture needed in biofuels applications.

CULTIVATION

Microalgae and cyanobacteria can be cultivated via photoautotrophic (where algae require light to grow and create new biomass) method in open or closed ponds or via heterotrophic method (where algae are grown without light and are fed a carbon source, such as sugars, to generate new biomass). Macroalgae (or seaweed) has different cultivation needs that typically require open off-shore or coastal facilities.

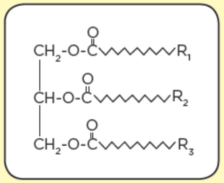
Designing an optimum cultivation system needs to leverage the biology of the algal strain used, as well as factor in the downstream processing options. Choices made for the cultivation system are key to the affordability, scalability, and sustainability of algae to biofuel systems.

Example Cultivation Systems

HARVESTING / DEWATERING

Some processes for the conversion of algae to liquid transportation fuels require pre-processing steps such as harvesting and dewatering. Algal cultures are mainly grown in water, which can require process steps to concentrate harvested algal biomass prior to extraction and conversion. These steps can be energy-intensive and can entail siting issues.

EXTRACTION



Algal Lipid: Precursor to Biofuels

Three major components can be extracted from algal biomass: lipids (including triglycerides and fatty acids), carbohydrates, and proteins. While lipids and carbohydrates are fuel precursors (e.g., gasoline, biodiesel and jet fuel), proteins can be used for co-products (e.g., animal/fish feeds).

Most challenges in extraction are associated with the industrial scale up of extraction system. While many analytical techniques exist, optimizing extraction systems that consume less energy than contained in the algal products is a challenge due to the high energy needs associated with both handling and drying algal biomass as well as separating out desirable products. Some algal biomass production processes are investigating options to bypass extraction, though these are also subject to a number of unique scale up challenges.

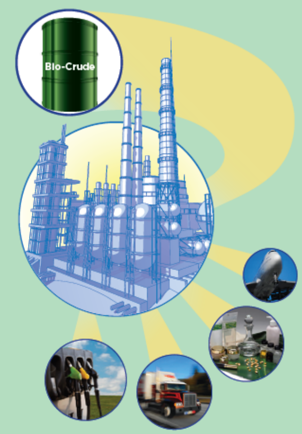
CONVERSION

Conversion to fuels and products is predicated on a basic process decision point:

1) Conversion of whole algal biomass;
2) Extraction of algal metabolites; or
3) Processing of direct algal secretions.

The conversion technologies may include chemical, biochemical, and thermochemical processes, or a combination of these approaches.

The end products vary depending on the conversion technology utilized. Focusing on biofuels as the end-product poses challenges due to the high volumes and relative low values associated with bulk commodities like gasoline and diesel fuels.



End Uses:

- Biodiesel
- Renewable Hydrocarbons
- Alcohols
- Biogas
- Co-Products (e.g., animal feed, fertilizers, industrial enzymes, bioplastics, and surfactants)

POLICY | SITING AND RESOURCES | REGULATIONS AND STANDARDS

Development Path Toward a Commercially Viable Algal Biofuel Industry

Algae R&D Challenges

Feedstock Biology, Cultivation, Harvesting & Dewatering

Source: DOE Algae Biofuels Technology Roadmap

	PROCESS STEP	R&D CHALLENGES
FEEDSTOCK	Algal Biology	• Sample strains from a wide variety of environments for maximum diversity • Develop small-scale, high-throughput screening technologies • Develop open-access database and collections of existing strains with detailed characterization • Investigate genetics and biochemical pathways for production of fuel precursors • Improve on strains for desired criteria by gene manipulation techniques or breeding
	Algal Cultivation	• Investigate multiple approaches (i.e., open, closed, hybrid, and coastal/off-shore systems; phototrophic, heterotrophic, and mixotrophic growth) • Achieve robust and stable cultures at a commercial scale • Optimize system for algal productivity of fuel precursors (e.g., lipids) • Sustainably and cost-effectively manage the use of land, water, and nutrients • Identify and address environmental risks and impacts
	Harvesting and Dewatering	• Investigate multiple harvesting approaches (e.g., sedimentation, flocculation, dissolved air floatation, filtration, centrifugation, and mechanized seaweed harvesting) • Minimize process energy intensity • Lower capital and operating costs • Assess each technology option in terms of overall system compatibility and sustainability

Algae R&D Challenges

Extraction, Fractionation, Conversion to Fuels & Co-products

Source: DOE Algae Biofuels Technology Roadmap

	PROCESS STEP	R&D CHALLENGES
CONVERSION	Extraction and Fractionation	• Investigate multiple approaches (e.g., sonication, microwave, solvent systems, supercritical fluid, subcritical water, selective extraction, and secretion) • Achieve high yield of desired intermediates; preserve co-products • Minimize process energy intensity • Investigate recycling mechanisms to minimize waste • Address scaling challenges, such as operational temperature, pressure, carrying capacity, side reactions, and separations
	Fuel Conversion	• Investigate multiple approaches to liquid transportation fuels (e.g., direct fuel production, thermochemical/catalytic conversion, biochemical conversion, and anaerobic digestion) • Improve catalyst specificity, activity, and durability • Reduce contaminants and reaction inhibitors • Minimize process energy intensity and emissions over the life cycle • Achieve high conversion rates under scale-up conditions
	Co-products	• Identify and evaluate the co-production of value-added chemicals, energy, and materials from algal remnants (e.g., biogas, animal/fish feeds, fertilizers, industrial enzymes, bioplastics, and surfactants) • Optimize co-product extraction and recovery • Conduct market analyses, including quality and safety trials to meet applicable standards

Algae R&D Challenges

Infrastructure and Cross-Cutting Analysis

Source: DOE Algae Biofuels Technology Roadmap

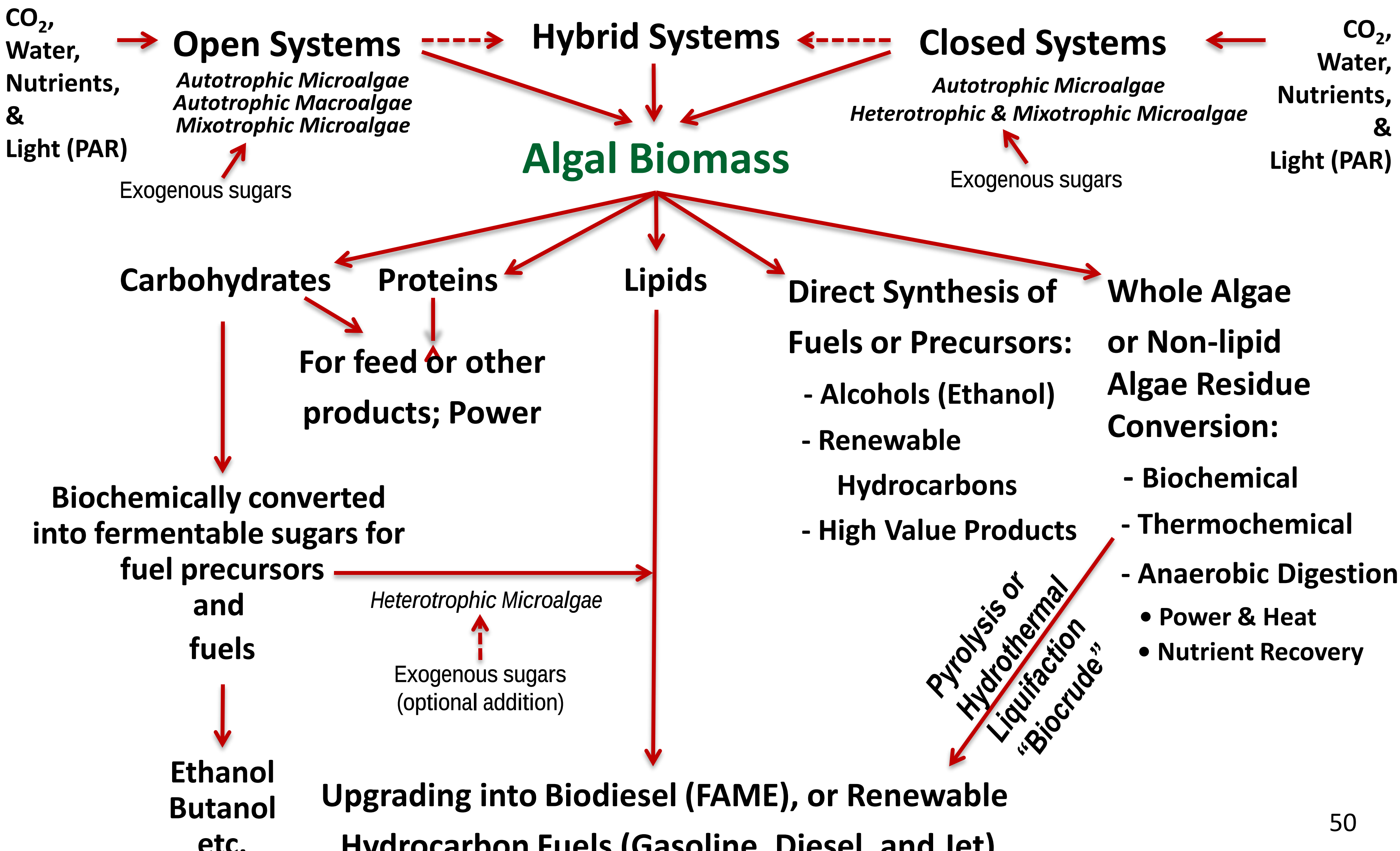
	PROCESS STEP	R&D CHALLENGES
INFRASTRUCTURE	Distribution and Utilization	• Characterize algal biomass, intermediates, biofuel, and bioproducts under different storage and transport scenarios for contamination, weather impacts, stability, and end-product variability • Optimize distribution for energy and costs in the context of facility siting • Comply with all regulatory and customer requirements for utilization (e.g., engine performance and material compatibility)
	Resources and Siting	• Assess and characterize land, climate, water, energy, and nutrient resource requirements for siting of microalgae (heterotrophic & photoautotrophic) and macroalgae production systems • Integrate with wastewater treatment and/or CO_2 emitter industries (in the case of heterotrophic approach) • Address salt balance, energy balance, water & nutrient reuse, and thermal management

PURSUING STRATEGIC R&D: TECHNO-ECONOMIC MODELING AND ANALYSIS

Given the multiple technology and system options and their interdependency, an integrated techno-economic modeling and analysis spanning the entire algae to biofuels supply chain is crucial in guiding research efforts along select pathways that offer the most opportunity to practically enable a viable and sustainable algae-based biofuels and co-products industry.

Algae Biofuels Pathways Summary

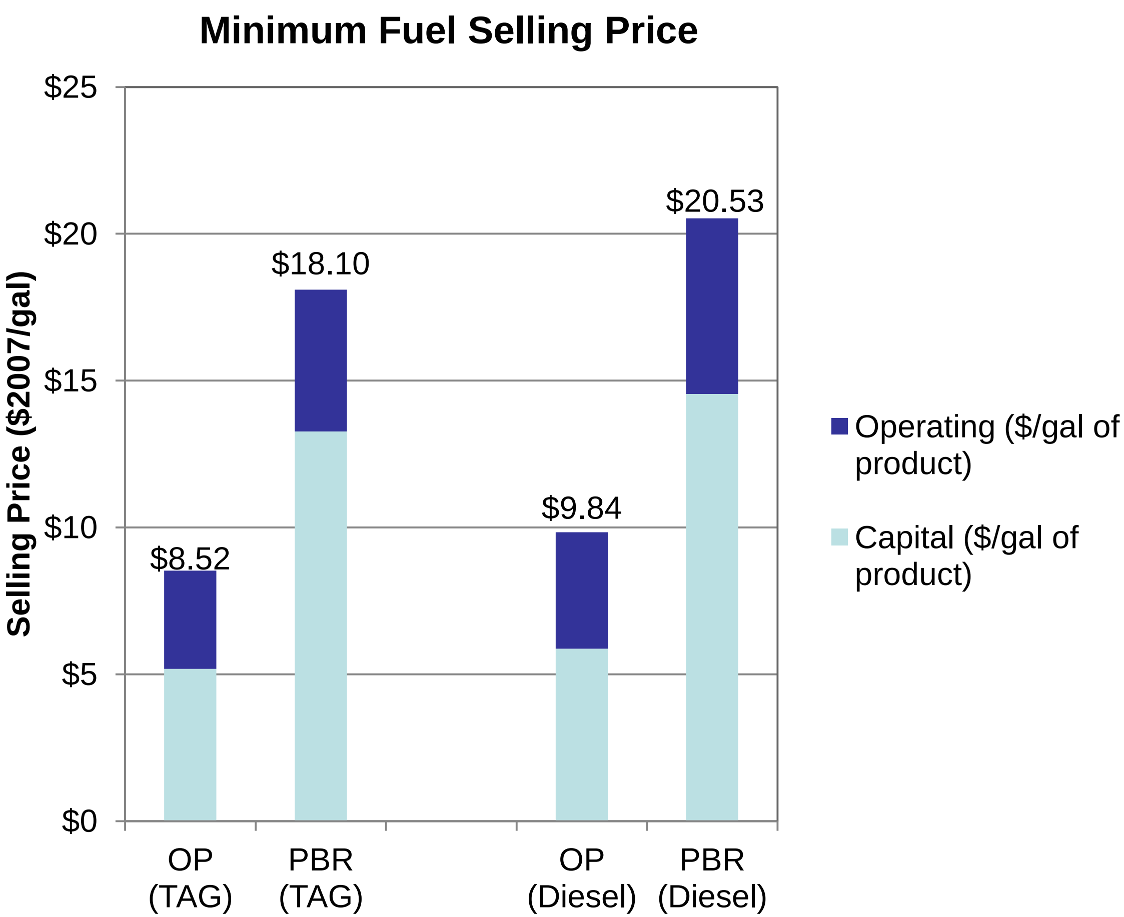
Production & Conversion to Fuels/Products

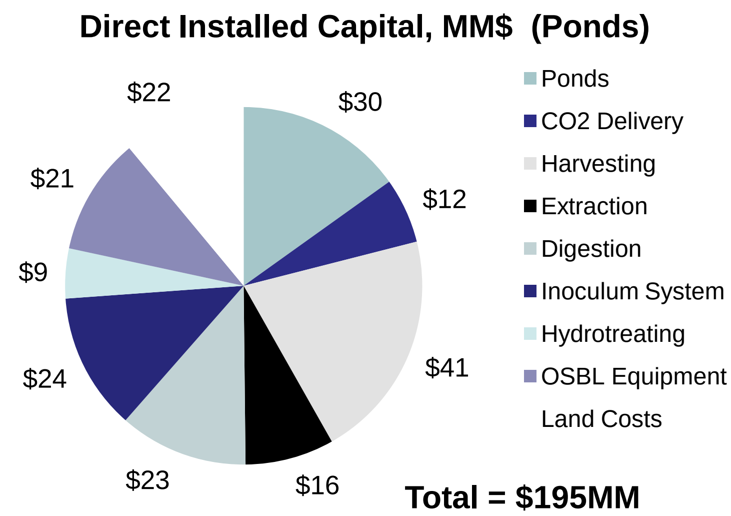


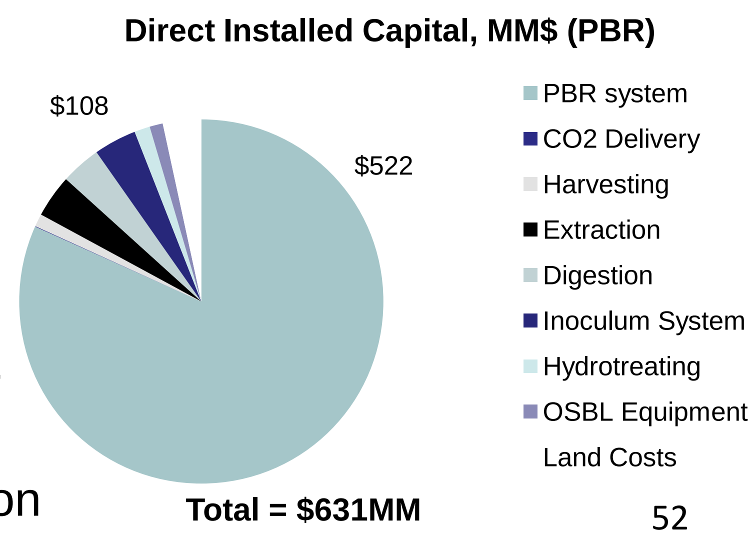
Heterotrophic Algae Approach
Considered a Conversion Process, Not a Primary Feedstock

- Heterotrophic algae oil production is a *biochemical conversion process*
  - *… Not a stand-alone feedstock derived directly from photosynthesis*
- Relies on an upstream source of organic carbon feedstock (e.g. sugars)
- Uses mature bioreactor (fermentation) technology capable of scale-up
- Controlled process enabling dense algae culture with high oil content
  - *… Culture densities of 50 to ≥ 150 grams/liter (dry weight)*
  - *… Oil content of 50% to ≥ 75% (dry weight basis)*
- Cost of production highly dependent on cost of sugar feedstock
- Has the same "sustainable feedstock" issues as today's ethanol biofuel
  - *… Food & Feed vs. Fuel issues can arise if commodity sugar or starch crops are used*
  - *… Will be most sustainable at large scale using C5 and C6 sugars from cellulosic biomass*
- Capable of biofuel feedstock oil scale-up in same manner as ethanol production, to extent that affordable feedstock sugars can be made available
- Life cycle assessment (LCA) and resource use impacts *(e.g., land, water, nutrients, energy, GHG)* must include the upstream sugar feedstock production
- Combination of heterotrophic with autotrophic (mixotrophic approach) can boost microalgae oil production using a dual metabolic path process

Autotrophic Algae Biofuels
Baseline Cost Analysis by NREL



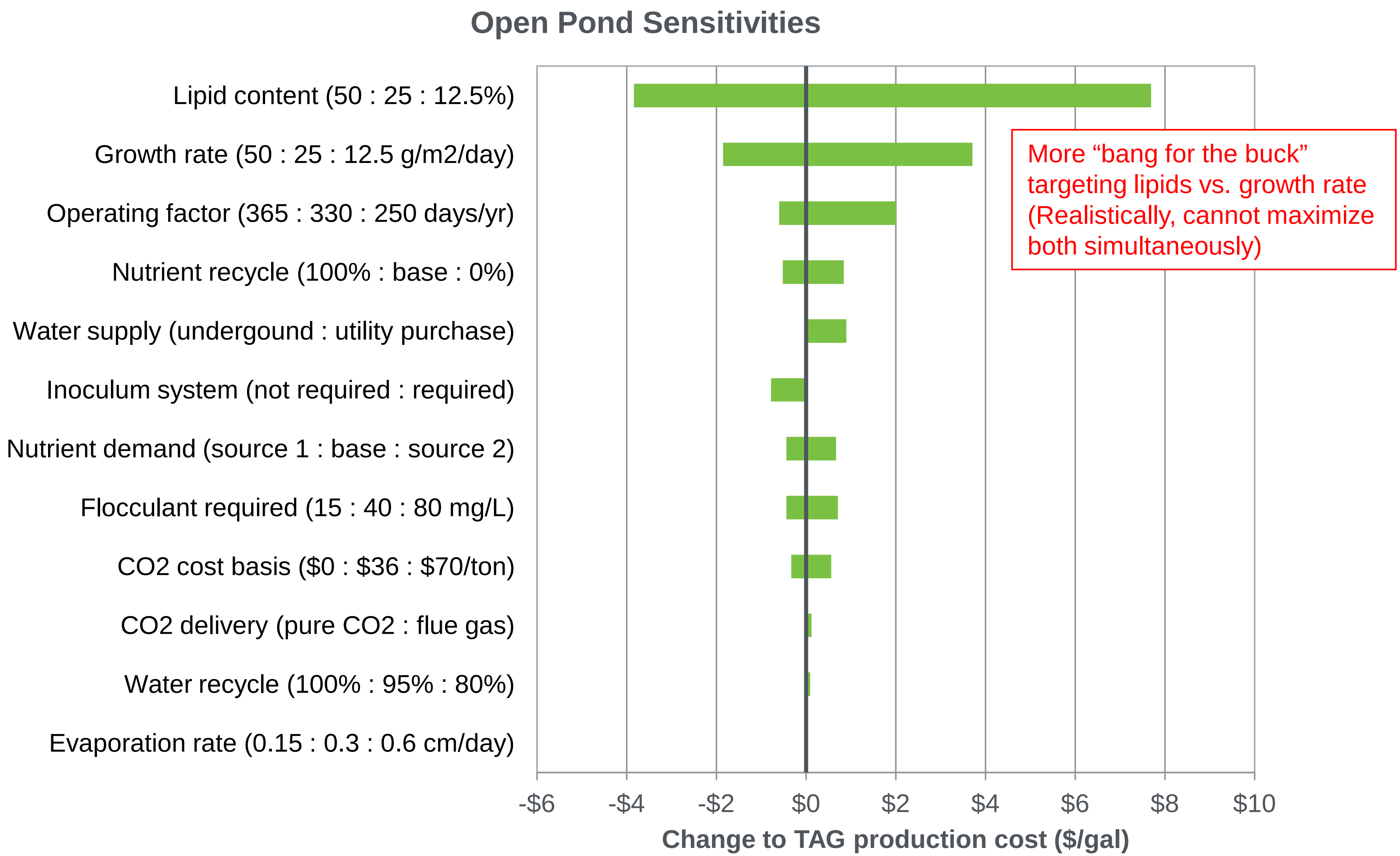




Baseline 2010 analysis (for 10 million gallons per year production scale) show high costs of today's currently available technologies & opportunities for cost reduction

NREL Baseline Cost Analysis Sensitivities

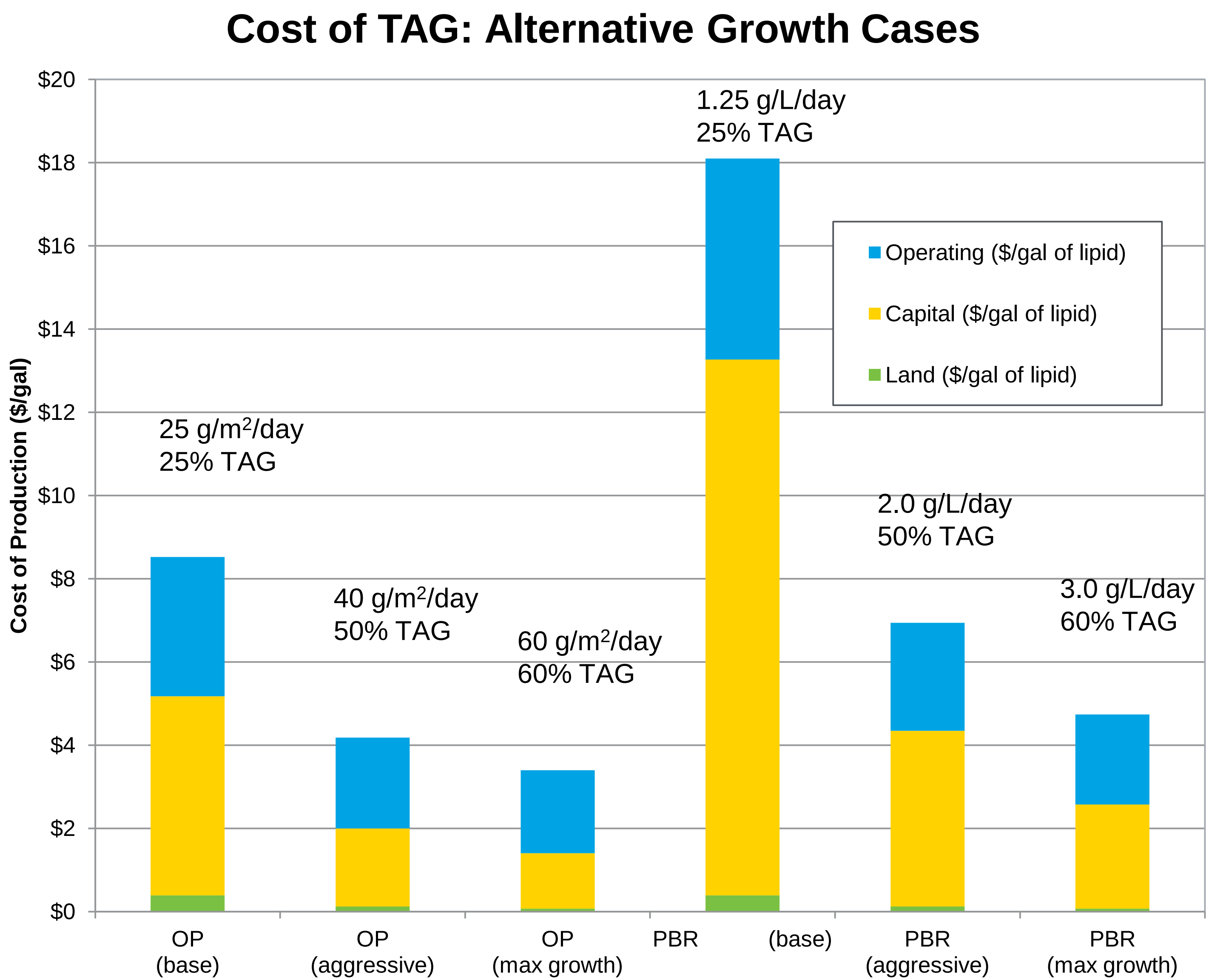
Sandia National Laboratories



[1] Benemann, J. et al., "Systems and Economic Analysis of Microalgae Ponds for Conversion of CO_2 to Biomass." Final Report to the Department of Energy, Pittsburgh Energy Technology Center (1996) DOE/PC/93204-T5

[2] Hassannia, Jeff. "Algae Biofuels Economic Viability: A Project-Based Perspective." Article posted online: http://www.biofuelreview.com/content/view/1897/1

NREL Baseline Cost Analysis Sensitivities



Systems Analysis Example - Algae Biofuels Scale-up
Scenario-Based Resource Demand Consequence Assessment

Sandia National Laboratories

Purpose: To address the following high-level questions …

- *How far can U.S. algae biofuels be sustainably scaled up?*
  - *To be relevant, fuel volumes must be significant in context of current & future U.S. demand for transportation fuels, and policy mandates for biofuels*
  - ***Must think in terms of many Billions of Gallons per Year (BGY)***
- *What are most likely resource constraints? … at what level?*
  - *Focus on land, water, CO_2, and nutrients (N, P)*
- *Can limitations be extended or overcome? … How?*

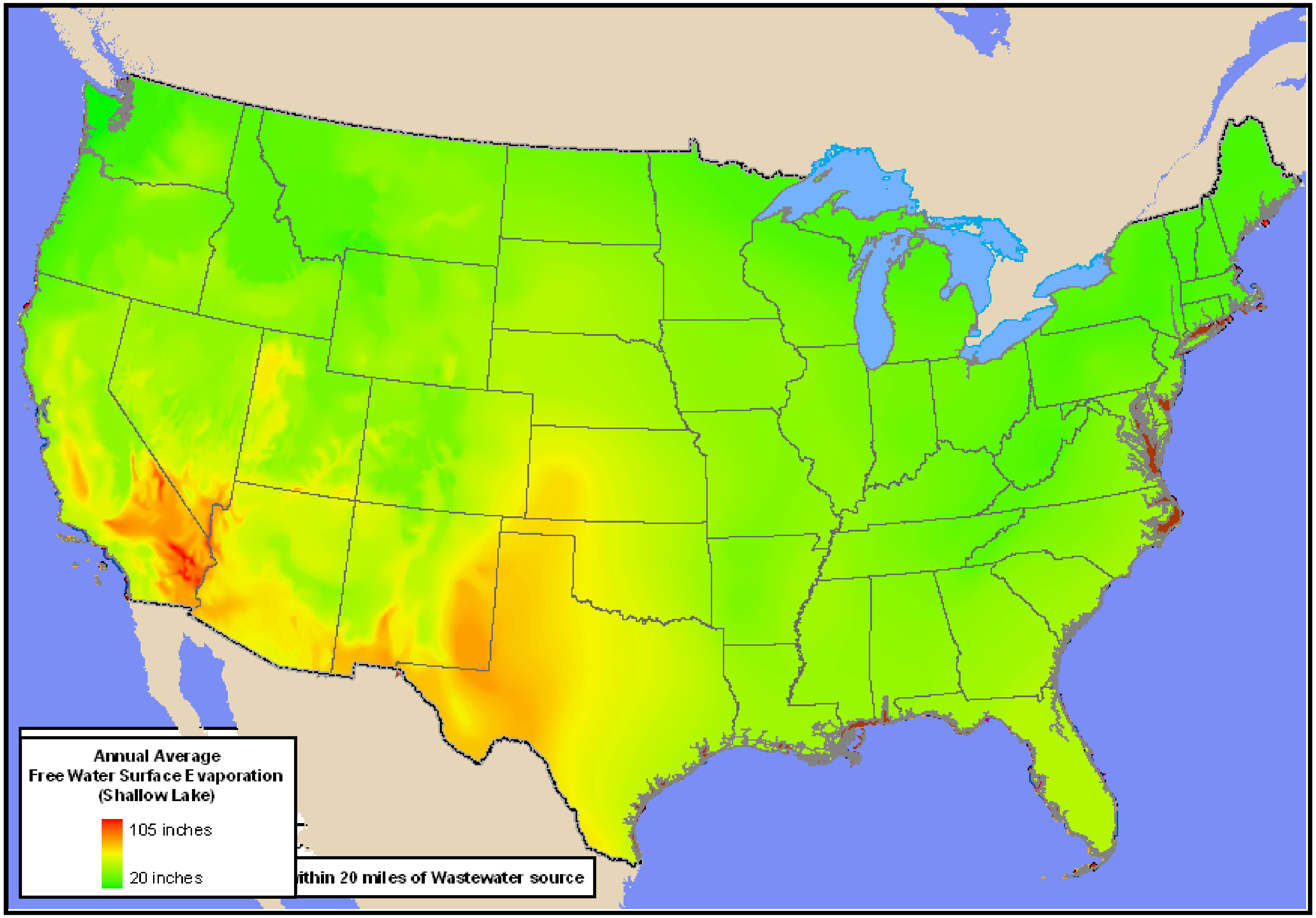
Goal: *To provide greater awareness and insight to technology developers and policy makers regarding the need to pursue promising algae biofuels approaches capable of sustainable build-up to significant fuel production on a national scale.*

SNL Algae Biofuels Scale-up Analysis
Scenario-Based Resource Demand Consequence Assessment

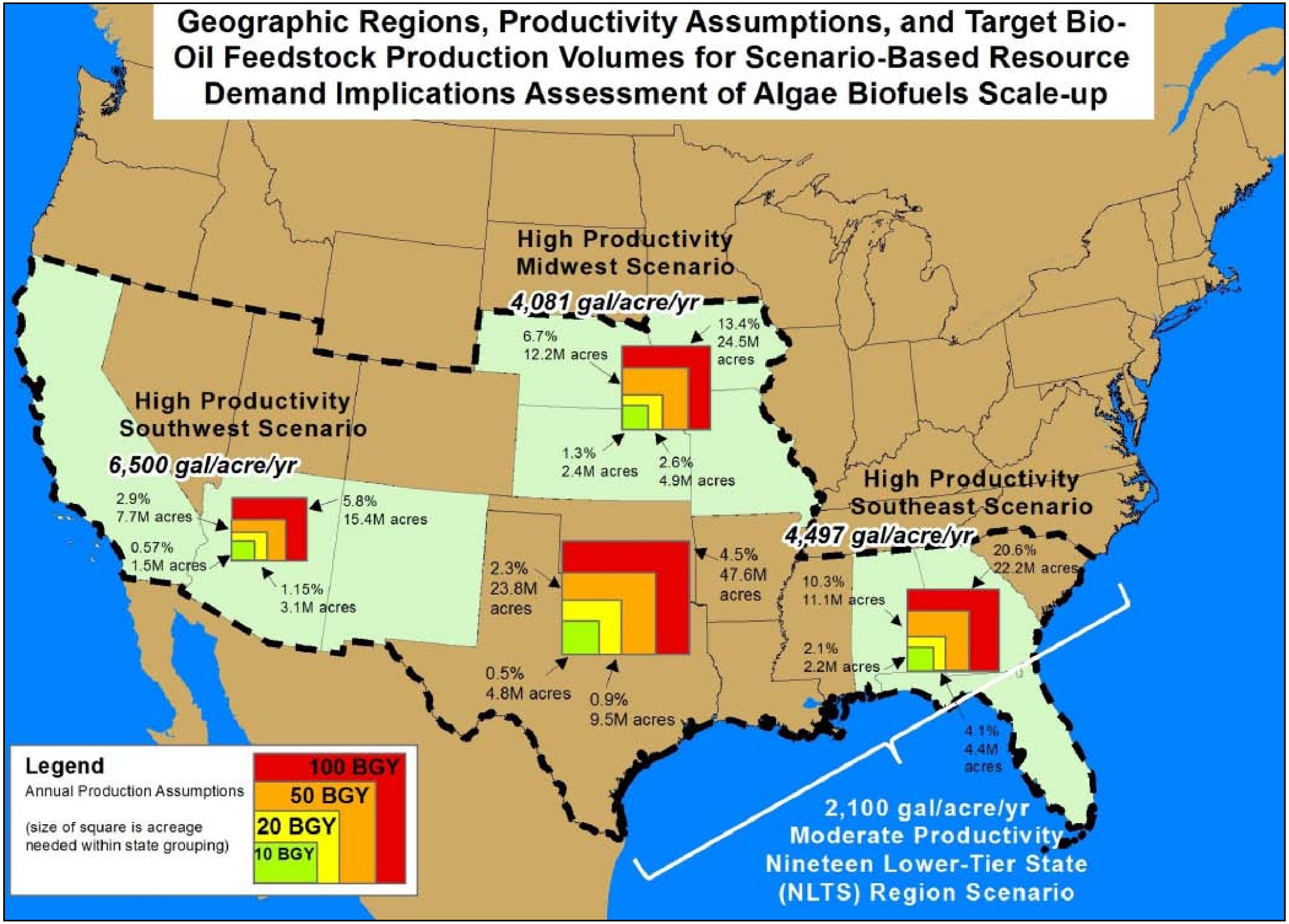
- Consider hypothetical algae production scale-up scenarios & locations in US
  - *- Target algal oil production levels of 10, 20, 50, & 100 BGY*
  - *- Ignore all systems and processes details … **assume it exists & works !***
- Assume range algae productivities … Moderate to Very Optimistic
  - *- Land requirements based on cultivation area needed for assumed productivity*
- Assume open system cultivation (subject to evaporative water loss)
  - *- Limit water demand estimate to evaporative loss only (ignore all other)*
  - *- Based on fresh water pan evaporation data … **likely to be worst case***
- Assume CO_2 and nutrient (N, P) demand based on simple mass balance with assumed algae C:N:P composition ratio and 100% utilization efficiency
- Compare projected land, water, CO_2 and nutrient (N, P) demand with estimates for resources available and/or similarly used
- Draw ***preliminary conclusions*** within limited scenario scope & assumptions

SNL GIS-based Preliminary Site Analysis

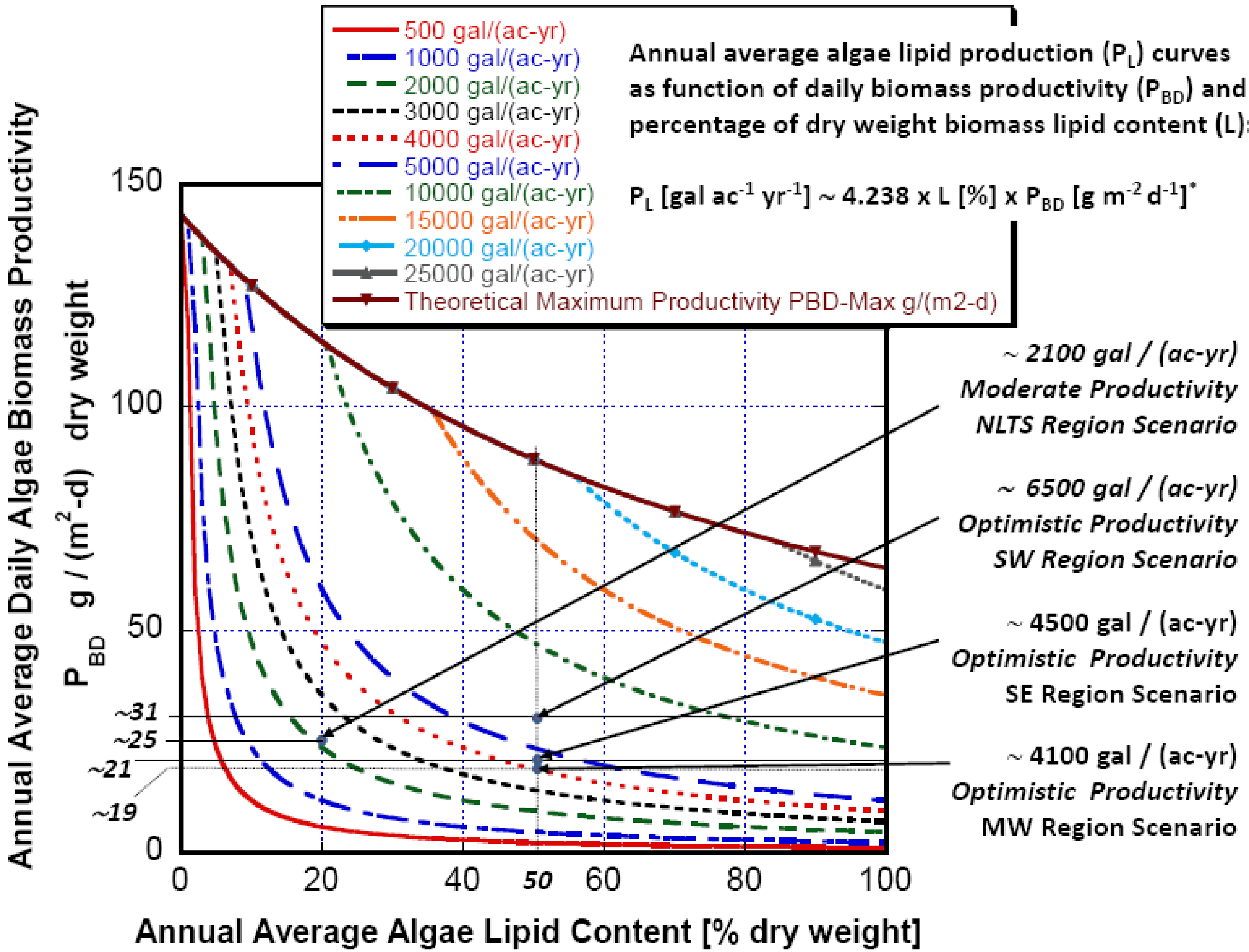
Identify Preferred Algal Biomass Production Site Locations



SNL Algae Biofuels Scale-up Scenarios

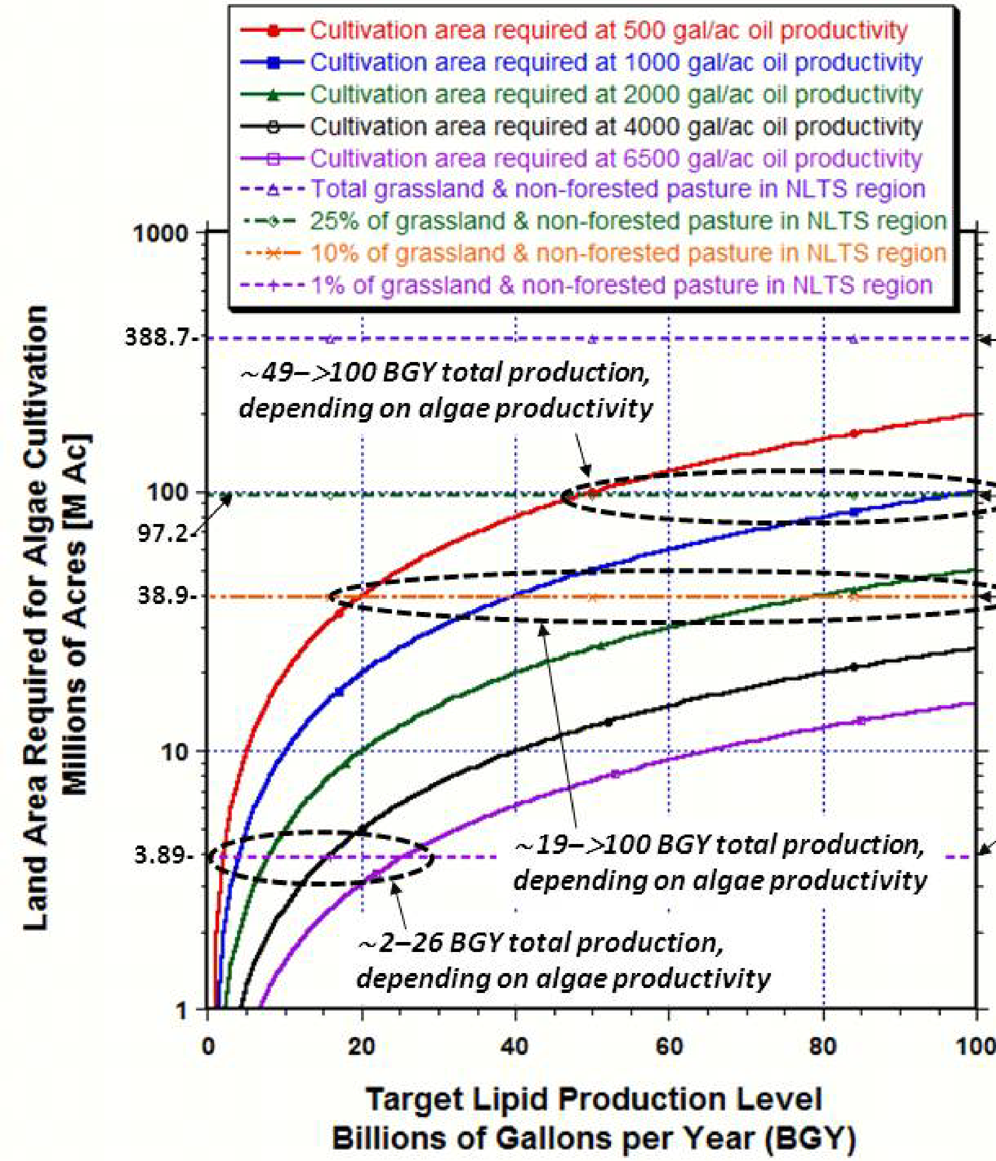


Algae Oil Productivity Curves as Function of Daily Biomass Productivity and Oil Content



* Cooney, Michael, Greg Young, and Ronald Pate (2010). "Bio-oil from photosynthetic microalgae: Case study", Bioresource Technology, 9 July.

Estimated Land Area Required
As function of target production & productivity levels



*Reference supply levels of grassland and non-forested pasture land selected as a suitable land use class for algae cultivation in the lower latitude NLTS Region of the US**

*Represents 100% of total grassland & non-forested pasture in NLTS region**

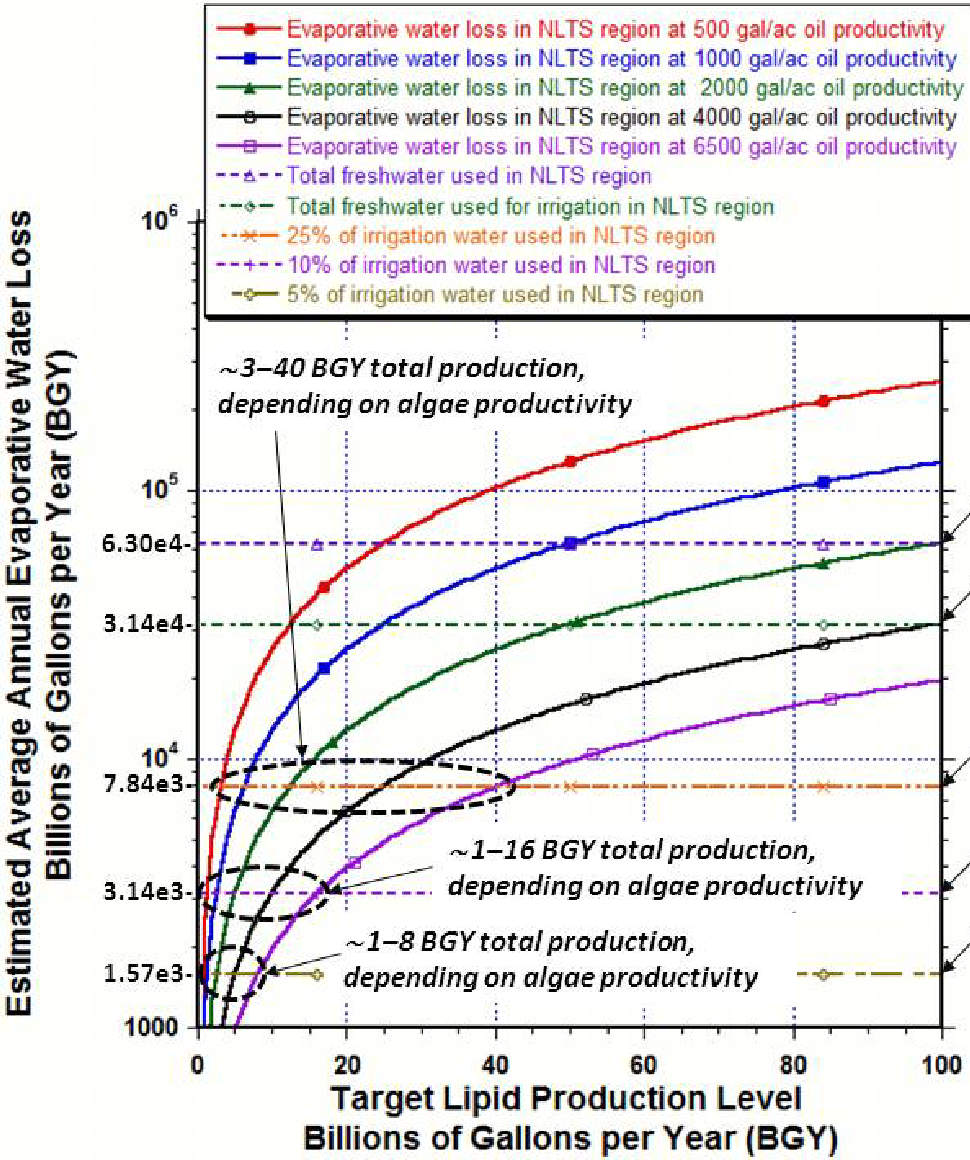
*Represents 25% of total grassland & non-forested pasture in NLTS region**

*Represents 10% of total grassland & non-forested pasture in NLTS region**

*Represents 1% of total grassland & non-forested pasture in NLTS region**

* As reported in:
USDA (2006). "Major Uses of Land in the United States, 2002", USDA Economic Research Service, Economic Information Bulletine Number 14.
http://www.ers.usda.gov/Data/MajorLandUses/MLUsummarytables.pdf

Estimated Water Required
As function of target production & productivity levels



*Reference supply levels of freshwater resources used in 2005 in the lower latitude NLTS Region of the US**. Irrigation is the most likely category of freshwater use that can be appropriated in sufficient volumes for growing algae**

*Represents total freshwater used for all purposes in the NLTS region**

*Represents 100% of total freshwater used for irrigation in the NLTS region**

*Represents 25% of total freshwater used for irrigation in the NLTS region**

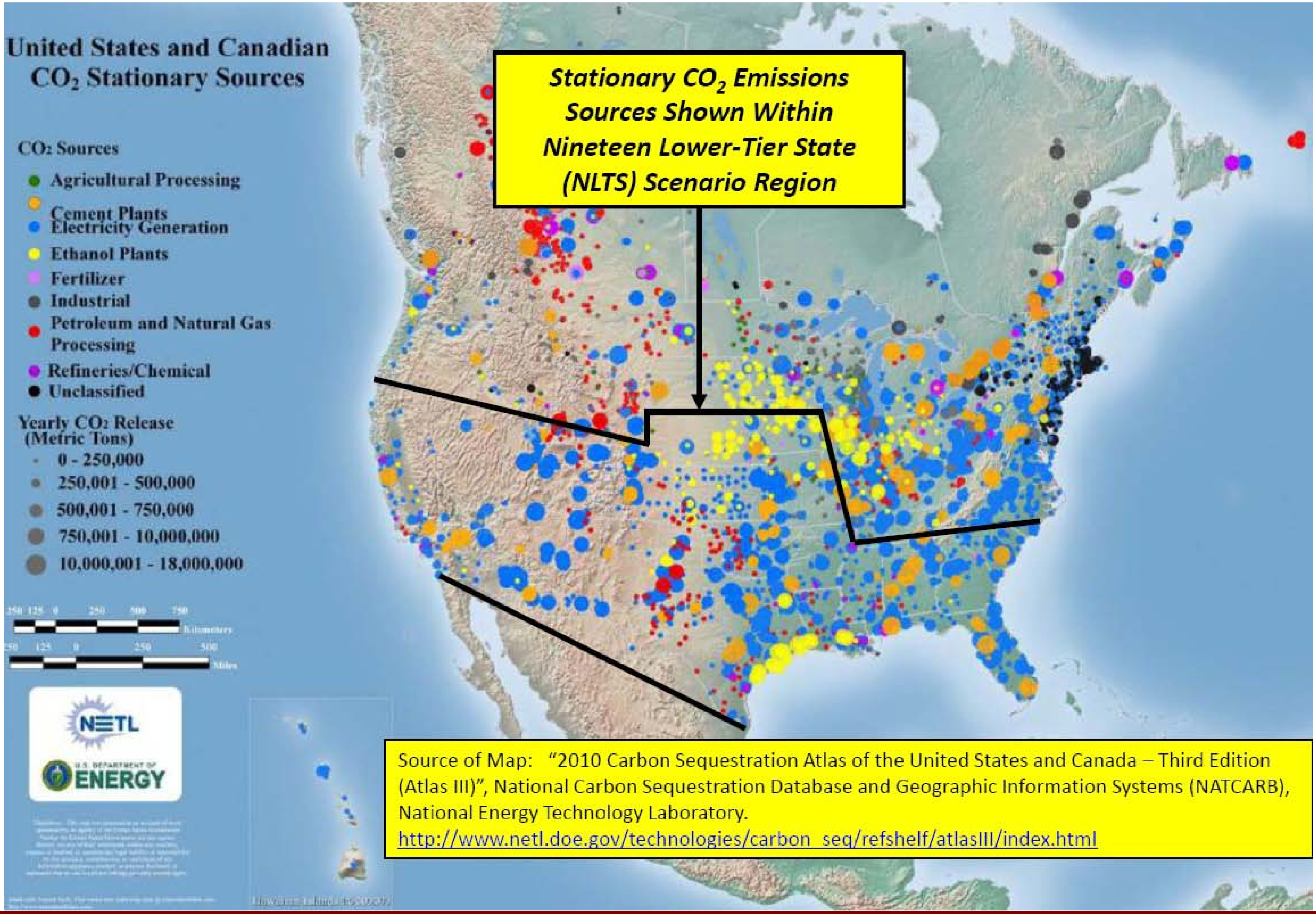
*Represents 10% of total freshwater used for irrigation in the NLTS region**

*Represents 5% of total freshwater used for irrigation in the NLTS region**

* Annual average evaporation rate for NLTS region estimated to be 47 inches per year, based on freshwater pan evaporation data: Farnsworth, R.K., E.S. Thompson, and E.L. Peck (1982). "Evaporation Atlas for the Contiguous 48 United States," NOAA Technical Report NWS 33, and "Evaporation for the United States", NOAA Technical Report NWS 34, Washington, D.C. http://www.weather.gov/oh/hdsc/PMP_related_studies/TR34.pdf

** Water use estimates for the US taken from: Kenny, J.F., N.L. Barber, S.S. Hutson, K.S. Linsey, J.K. Lovelace, and M.A. Maupin (2009). "Estimated Use of Water in the United States in 2005", USGS Circular 1344. http://pubs.usgs.gov/circ/1344/.

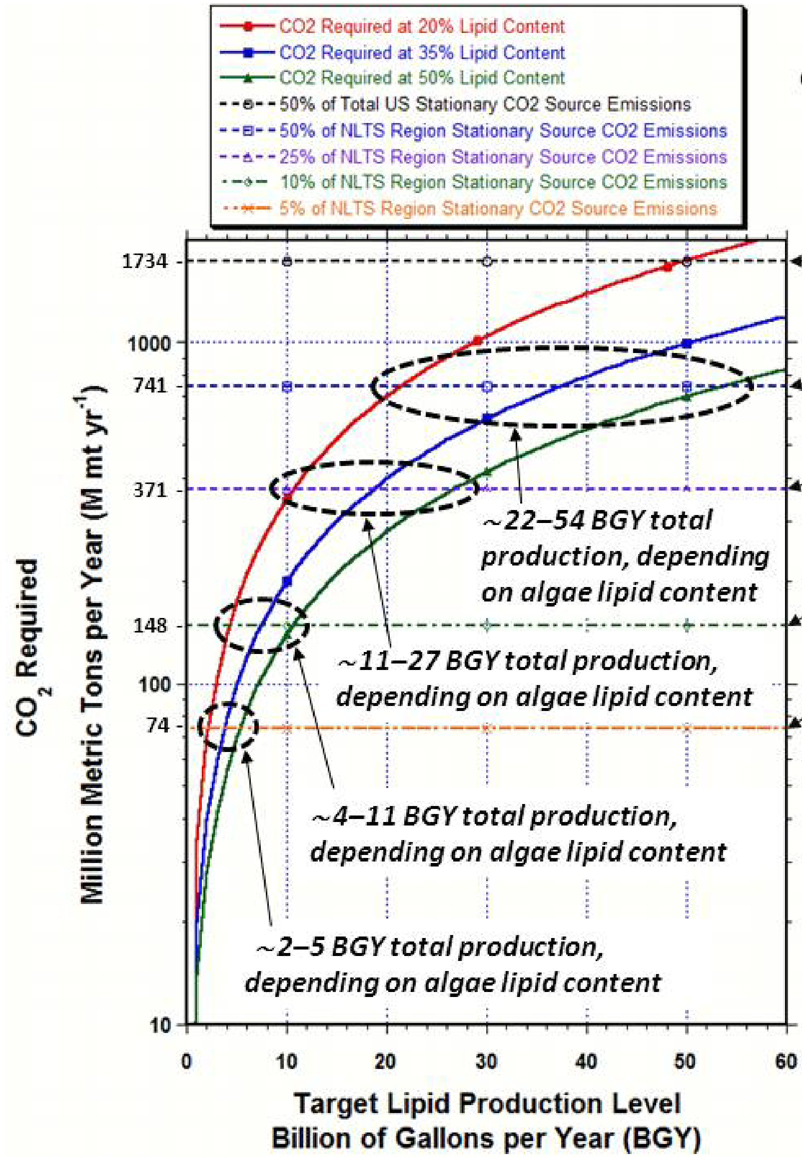
Stationary CO_2 Emission Sources *in Lower-Tier State Scenario Region*



Source of Map: "2010 Carbon Sequestration Atlas of the United States and Canada – Third Edition (Atlas III)", National Carbon Sequestration Database and Geographic Information Systems (NATCARB), National Energy Technology Laboratory.
http://www.netl.doe.gov/technologies/carbon_seq/refshelf/atlasIII/index.html

Estimated CO_2 Required

As function of target production & productivity levels



Reference supply levels of *daylight hour* CO_2 emissions in 2008 from stationary emitter sources*

*Represents 50% - 100% of total daylight hour emissions in the entire US**

*Represents 50% - 100% of total daylight hour emissions in the NLTS Region**

*Represents 25% - 50% of total daylight hour emissions in the NLTS Region**

*Represents 10% - 20% of total daylight hour emissions in the NLTS Region**

*Represents 5% - 10% of total daylight hour emissions in the NLTS Region**

* Baseline assumption is that annual average CO_2 emissions from stationary sources are evenly spread over 24 hours per day, 7 days per week, 365 days per year, with daylight hours taken as 12 hours per day, resulting in daylight hour emissions being 50% of total emissions. The most optimistic alternative CO_2 availability assumption would be that all stationary sources operate and emit only during daylight hours, resulting in daylight hour emissions being 100% of total emissions. The reference lines shown above reflect this estimated range of daylight emissions to total emissions. Stationary source CO_2 emissions data was taken from the NETL NATCARB data base, which only provides annual totals by state and type of source: http://www.netl.doe.gov/technologies/carbon_seq/natcarb/index.html

Estimated Nitrogen Required
As function of target production & productivity levels

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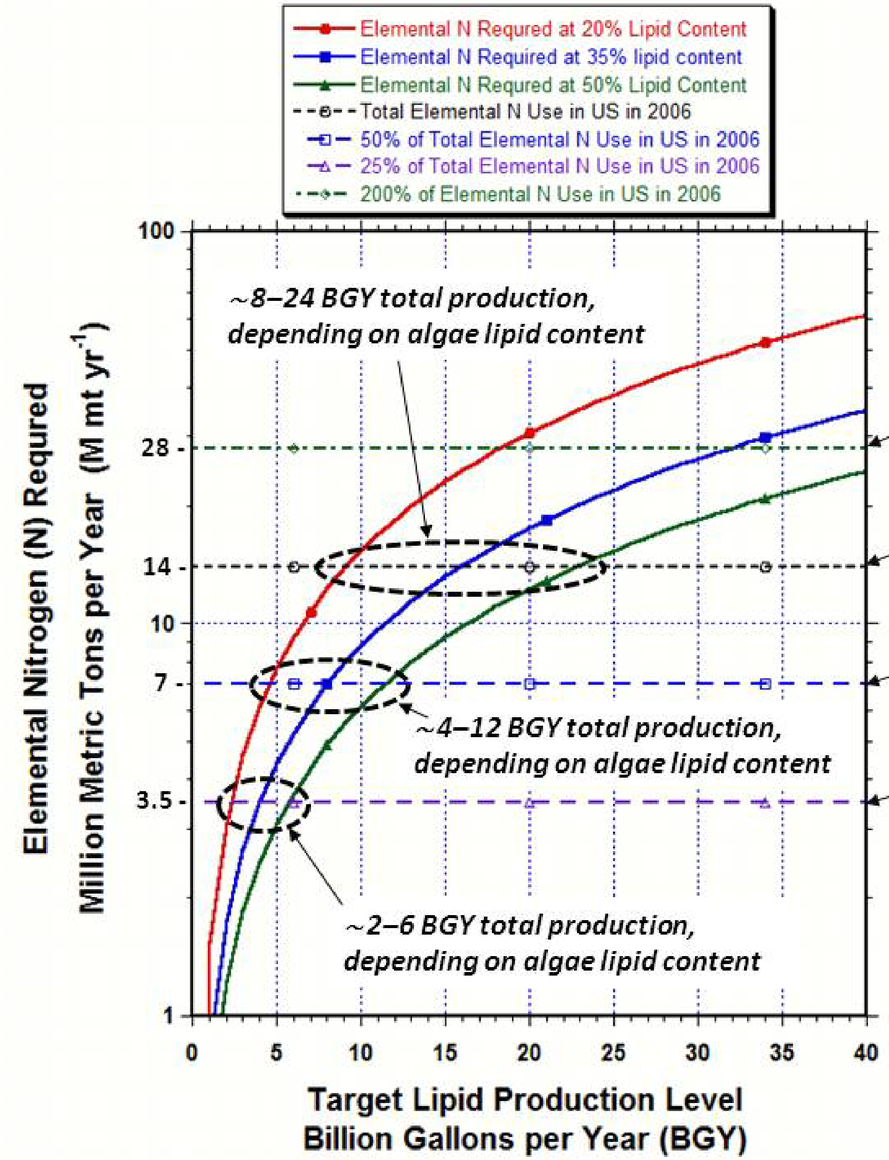


*Reference supply levels of elemental Nitrogen (N) based on U.S. use as ammonia in 2006**

*Represents 200% of total elemental Nitrogen (N) in ammonia used in the US in 2006**

*Represents 100% of total elemental Nitrogen (N) in ammonia used in the US in 2006**

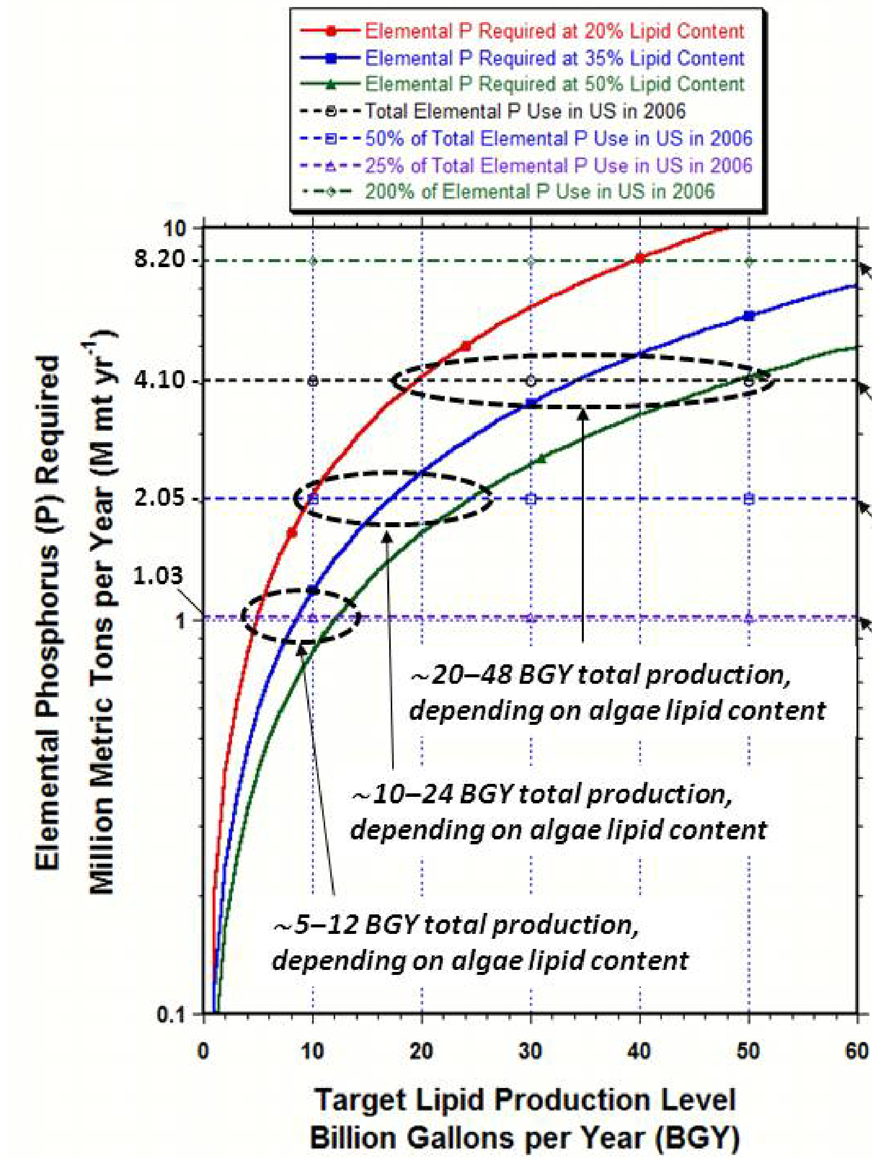
*Represents 50% of total elemental Nitrogen (N) in ammonia used in the US in 2006**

*Represents 25% of total elemental Nitrogen (N) in ammonia used in the US in 2006**

* As reported in:

- USGS, "Mineral Commodity Summaries 2010", U.S. Geological Survey, U.S. Department of Interior, 2010 http://minerals.usgs.gov/minerals/pubs/myb.htm
- USGS, "Minerals Yearbook", U.S. Geological Survey, U.S. Department of Interior, 2010 http://minerals.usgs.gov/minerals/pubs/mcs/2010/mcs2010.pdf

Estimated Phosphorus Required
As function of target production & productivity levels



Reference supply levels of elemental Phosphorus (P) based on U.S. use as phosphate rock in 2006*

*Represents 200% of total elemental Phosphorus (P) in phosphate rock used in the US in 2006**

*Represents 100% of total elemental Phosphorus (P) in phosphate rock used in the US in 2006**

*Represents 50% of total elemental Phosphorus (P) in phosphate rock used in the US in 2006**

*Represents 25% of total elemental Phosphorus (P) in phosphate rock used in the US in 2006**

* As reported in:

- USGS, "Mineral Commodity Summaries 2010", U.S. Geological Survey, U.S. Department of Interior, 2010 http://minerals.usgs.gov/minerals/pubs/myb.htm
- USGS, "Minerals Yearbook", U.S. Geological Survey, U.S. Department of Interior, 2010 http://minerals.usgs.gov/minerals/pubs/mcs/2010/mcs2010.pdf

SNL Algae Scale-Up Assessment
Summary of *Resource Demand Implications*

- **Land** … requirements probably manageable for high scale-up
- **Water** … significant challenge with limited freshwater resources
  - *Can't plan on big national scale-up using freshwater with evaporative loss*
  - *Need approaches that use marine and other non-fresh waters*
  - *Need Inland approaches that can reduce evaporative loss (closed systems?)*
  - *Open system salinity build-up with non-fresh waters will be issue for inland sites*
- **Nutrients (N & P)** … significant challenge
  - *Could seriously compete with agriculture and other commercial fertilizer uses*
  - *Cost and sustainability are issues for commercial fertilizer use*
  - *Need approaches enabling cost-effective nutrient capture and recycling*
- **CO_2 Sourcing** … significant challenge
  - *How much from stationary emitters can be affordably tapped and utilized?*
  - *Co-location opportunities vs. affordable range for transporting concentrated CO_2?*
  - *Can other sources and/or forms of inorganic carbon be affordably used?*
- **Based on Assessment Scenario Assumptions and Trends**
  - *Resource constraints likely to emerge within the 5 to 15 BGY oil production range*
- ***Constraint reduction possible with innovation***
  - *Resource use intensity improves with increased algae productivity & oil content*
  - *How much can this be improved for reliable large scale operations? … TBD !*

Conclusions

- Numerous Alternative Fuels Options Exist, Each with Pros & Cons
  - Non-Renewable Energy Minerals
    - Most High-Carbon Footprint Unless Carbon Capture & Storage Implemented
    - Used for Electric Power Production and Liquid Hydrocarbon Transport Fuels
  - Electrification of the Light Vehicle Fleet (not suitable for aviation & heavy transport)
    - Carbon Footprint Depends on the Form of Electric Power Generation Used
    - EVs Save on Life Cycle Fuel Costs at the Penalty of Higher Initial Vehicle Cost
    - Infrastructure, Cost, and Battery Energy Density Issues are Challenges
  - Renewable Power and Liquid Transportation Fuels From Renewable Sources
    - Fuel Options and Flexibility Greatest with Biomass
    - Potential Emerging Technology for Liquid Fuel Production from Solar Thermal (S2P)
- Key Issues that come into play are
  - Scale-up Potential
  - Sustainability
  - Affordability
  - Compatibility with Existing Infrastructure
- All Options Involve Complex Systems Interdependencies within the Context of the Broader Energy-Water-Land-Climate Nexus

Sandia National Laboratories

Key Information Sources

DOE/EERE Alternative Fuels & Advanced Vehicles Data Center

http://www.afdc.energy.gov/afdc/fuels/index.html

DOE/EERE Office of Biomass Program

http://www.biomass.energy.gov

The U.S. Department of Energy Biomass Program produces a variety of publications focused on applied biomass and biofuels technologies including factsheets, reports, case studies, presentations, analyses, and statistics. To learn more visit: www.biomass.energy.gov/pdfs/publications.pdf

or the Biomass Publication and Product Library at www.biomass.energy.gov/publications.html

DOE Office of Science

http://science.energy.gov/

DOE/EERE Office of Biomass Program 2011 Review Reports

Reports are now posted live on Biomass Program Website

http://www1.eere.energy.gov/library/pir_publicationsnew.aspx/page/1

Program Peer Review Report:

www.eere.energy.gov/biomass/pdfs/2011_program_review.pdf

Platform Peer Review Reports:

1. IBR Platform Review: www.eere.energy.gov/biomass/pdfs/2011_ibr_review.pdf
2. Infrastructure Platform Review: www.eere.energy.gov/biomass/pdfs/2011_infrastructure_review.pdf
3. Biochemical Conversion Platform Review:
   www.eere.energy.gov/biomass/pdfs/2011_biochem_review.pdf
4. Thermochemical Conversion Platform Review:
   www.eere.energy.gov/biomass/pdfs/2011_thermochem_review.pdf
5. Analysis Platform Review: www.eere.energy.gov/biomass/pdfs/2011_analysis_review.pdf
6. Sustainability Platform Review: www.eere.energy.gov/biomass/pdfs/2011_sustainability_review.pdf
7. Feedstock Platform Review: www.eere.energy.gov/biomass/pdfs/2011_feedstocks_review.pdf
8. Algae Platform Review: www.eere.energy.gov/biomass/pdfs/2011_algae_review.pdf

THANK YOU!

QUESTION & ANSWER SESSION

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