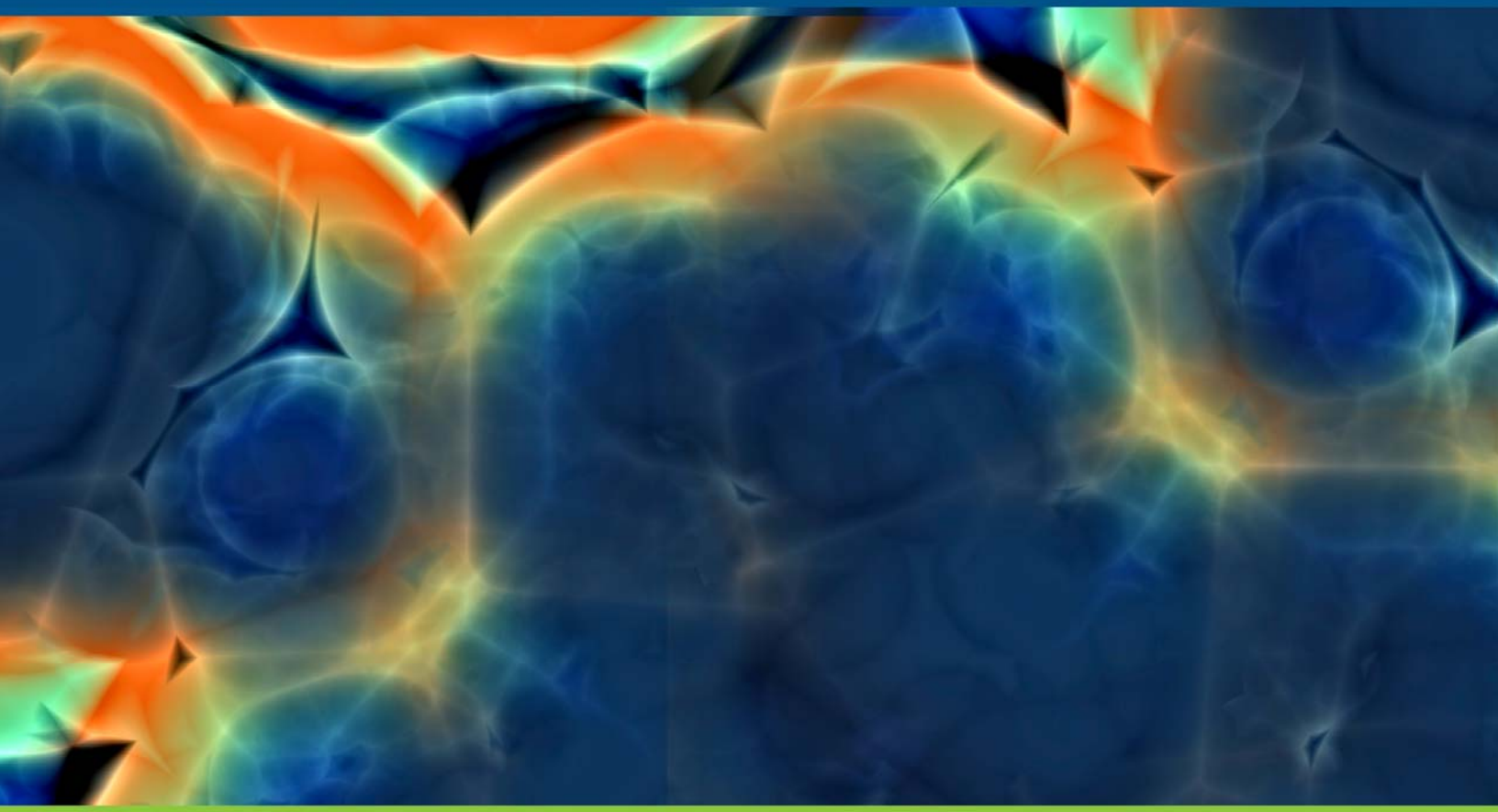
U.S. DEPARTMENT OF ENERGY BIOMASS PROGRAM



Algal Biofuels Technical Roadmap
Workshop Summary

December 9 – 10, 2008

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Introduction

The Algal Biofuels Technology Roadmap Workshop, held December 9 and 10, 2008, was convened by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Office of the Biomass Program to receive comments on potential barriers to establishment of a domestic, commercial-scale algae-based biofuels industry and strategies to realize this goal. More than 200 participants provided experience and expertise during a series of technical discussions spanning all aspects of the challenge. Algal science and engineering topic areas included biology, production, processing and conversion. Additionally, techno-economic modeling; siting; the acquisition and/or capture, use and recycling of resources; policy; regulations; co-products and financial needs were discussed.

This document is a summary of the individual comments received during the technical breakout sessions attended by industry, academia and laboratory experts. This summary should not be considered a comprehensive account of the workshop: the workshop results will be fully documented in the "National Algal Biofuels Technology Roadmap" expected to be completed by the Office of the Biomass Program in the summer of 2009.

Techno-Economic Modeling

Commenters stated that techno-economic modeling is an essential capability needed for guiding, tracking, and providing decision-support to enable the development of affordable, scaleable, environmentally and socially sustainable algal biofuels. The ultimate goal of techno-economic modeling is to use information gathered and integrated from multiple sources to inform R&D, policy and business development decisions.

Commenters stated that techno-economic modeling and analysis challenges for algal biofuel production include the need to carefully assess requirements for land, water, CO_2 and other nutrient use and consider issues of scale, alternative production technologies, externalities, and fuel and other co-product markets. Furthermore, comments stated that validated parameters describing fundamental biological, physical and chemical processes, systems, and costs involved in unit operations at scale for algal biomass feedstock production and downstream processing into biofuels and co-products are largely lacking. Drawing on lessons learned from hydrogen and cellulosic ethanol techno-economic models, suggested priorities from individual commenters include:

- Definition of requirements, metrics, and standards for comparative modeling and analyses of alternative systems and processes approaches for algal biofuels
- Development of models for alternative algal biofuel production systems, processes, and implementation scenario pathways suitable for comparative analyses of technical, economic, and environmental impact performance
- Collection and validation of inclusive, transparent and sometimes business sensitive data
- Commitment to transparent model creation and explicit communication of model assumptions and boundaries.

Participants suggested that the systems integration challenges of developing an algal biofuels industry call for the establishment of demonstration-scale facilities to validate models, generate data and provide guidance on future research and policy.

Feedstock Development and Production

Many challenges hindering the commercial production of algal biofuels are interdependent, especially with respect to algal biology, cultivation, and siting/resource needs. Thus, comments focused on an integrated approach to address these intertwined feedstock challenges.

Commenters stated that, compared to biomass derived from domesticated crops or forests, algal biomass development and production not only lack an extensive agricultural history to help inform current R&D efforts, but pose additional unique challenges as aquatic organism cultivation systems. This workshop targeted comments on feedstock development with emphasis on algal biology topics spanning three areas: 1. strain isolation and screening; 2. cell biology; and physiology; and 3. genomics and systems biology. Subsequently, algal production discussions focused on two main topics: cultivation, and siting and resources.

Algal Biology: Improving Strain Characteristics

Comments stated that fundamental research into improving the commercial potential of algal cultivars is a foundational piece of developing a viable algal biofuel pathway. Strain improvement comments covered three topics in which basic and applied science investments were identified. Participants noted that the field is fragmented and lacks basic dedicated research infrastructure ranging from unified culture collection databases to genome sequencing and annotation capabilities to pilot cultivation facilities. Participants' statements indicated that these studies could benefit from a set of rigorous standards. Uncertainties and lack of data on growth requirements, growth rates, photosynthesis, lipid production, cell wall composition and ultrastructure walls, and cultivar robustness and consistency of strains, were identified by commenters as major barriers to an accurate techno-economic modeling effort.

Strain Isolation and Screening

The aim of isolation and screening efforts is to identify and maintain promising algal specimens for cultivation and strain development. Commenters stated that challenges range from a lack of clarity over key characteristics for which to screen (i.e., triacylglycerides and/or other hydrocarbons) and the variability of *in situ* versus laboratory specimens to how to quantify consistency, resilience, and community stability for unknown production systems. Additional unknowns identified by commenters were how to screen excreted materials as well as the suitability of macroalgae as a biofuels feedstock. Three priorities identified by commenters are:

- Development of screening standards and creation of an effective high-throughput screening methodologies that can identify promising strain characteristics
- Improvement of resources for standards and public culture collections and create a public database infrastructure on strains and their characteristics
- Development of baseline data on the effects of regional environmental variability on cultivars.

Cell Biology/Physiology

The basic premise of algal cell biology research is to understand, manipulate and improve the cellular processes that control growth, carbon partitioning, and lipid production. Comments covered challenges in lipid metabolism and its regulation, photosynthesis, carbon partitioning, and stress responses in relation to lipid production. Priorities identified in comments can be broadly summarized in four categories:

- Understanding lipid metabolism, specifically identification of housekeeping and alternative lipid synthesis pathways and their regulators and enhancement of lipid production
- Investigating photosynthetic carbon partitioning, particularly into storage lipid under various environmental and culture conditions
- Investigating molecular and cellular mechanisms and the physiological role of storage neutral lipid accumulation and lipid body formation
- Manipulation of carbon partitioning for lipid storage and decoupling of cell division and lipid formation

Genomics and Systems Biology

The genomics/systems biology approach aims to take advantage of advances in the "omics" technologies to investigate and manipulate gene expression and biochemical pathways in algae. Comments covered challenges in establishing appropriate model systems and research infrastructure to annotate sequenced genomes and the lack of a fundamental understanding of algal metabolic pathways. Priorities identified in comments included the following:

- Selection of at least two (at least one green and one diatom) to five algal model systems
- Development of robust criteria for selecting algal organisms for genome sequencing and annotation efforts methods
- Establishment of an integrated systems biology & bioinformatics framework to develop a fundamental understanding of carbon partitioning in algae
- Development of next generation genetic tools and synthetic biology systems for algae

Cultivation

Algal cultivation focused on the challenges of both cultivating algae for biofuels and modeling cultivation scenarios to improve processes. While the comments focused on phototrophic microalgal systems grown in open ponds or photobioreactors, some commenters indicated that that alternative cultivation systems such as heterotrophic production, macroalgal cultivation and open ocean cultivation also hold promise. Based on comments, the role of growth media was seen as especially important in the interface between algal biology research and variable cultivation schemes being pursued by algal biofuel companies. Based on comments, the role of nutrients such as nitrogen, phosphorous and minerals emerged as a particularly salient aspect, and clarification of the impacts of growth media on algal growth and production is also needed for better techno-economic modeling. Priorities identified by commenters included:

- Research on culture stability (e.g. pathogenicity, predation) and minimizing downtime
- Research on microbial ecology to address monocultures vs. mixed communities
- Standardization of measures and protocols for algal productivity, yields, rates, densities and metabolites
- Research on nutrient management issues including utilization of municipal and agricultural waste streams
- Research into management of evaporative water loss, water sourcing, water recycling and maintenance of appropriate salinity levels
- Establishment of a mechanism for cooperative sharing of real-world data

Cultivation was recognized in comments as an important and applied interface among biology, processing, and techno-economic modeling and it was recommended that feedbacks between cultivation and these areas be incorporated in production schemes.

Siting and Resources

The scope of comments about siting and resources was limited to identifying key issues, challenges, and strategies that could be addressed with Department of Energy (DOE) investment. Commenters stated that assumptions about siting and resources are difficult to make because the field of algal biofuels is immature, and lacks quantitative data necessary to model trade-offs in siting and resource-use decisions. Also noted was the fact that numerous siting and resource utilization issues are outside the direct purview of DOE or involve overlap with the interests and missions of other federal and state agencies and non-governmental organizations (NGOs). Specific milestones identified by commenters for DOE involvement were: 1) the provision of objective technical and economic data and assessments regarding the availability, scale-up feasibility, costs, and impacts due to use of resources such as land, CO_2-containing flue gas and other waste streams, fresh and non-fresh water resources that include

saline aquifers and wastewater/agricultural runoff, other sources of nutrients (e.g., N,P,K), and impact of local climate and weather conditions for algal biofuel production in both large centralized and smaller distributed operations; 2) the development of technologies to integrate algal biofuel and co-product facilities with wastewater treatment and CO_2 emission sources, in proximity to fuel and other co-product markets; and 3) the pursuit of strategic partnerships with other federal and state agencies, industry, other NGOs, and universities to leverage overlapping technical and policy interests and to facilitate both technical and human resource development.

Processing and Conversion

Processing represents the integration of cultivating algal products and conversion to fuels. The processing topic area covered technical barriers to harvesting and extracting algal products such as lipids, co-products, or residual biomass from the cultivation system.

The scope of comments in the conversion topic included identifying technical barriers in fuel production as well as integrating co-product production with algal biofuel operations. Comments indicated a perceived need for the creation of an extensive database of algal biomass composition coupled with fuel conversion inputs and outputs as a function of technology, as well as the need to retain maximum value of residual biomass streams.

Harvesting

Comments of harvesting gravitated around setting harvesting and dewatering target dry-weight goals. However, comments indicated that setting these goals was challenging because they depend on cultivation system engineering and integration, and there is no consensus on the best cultivation systems. Regardless of the dry-weight target, research and development priorities needs were identified by commenters. Process engineering suggestions included unit operation analysis of energy inputs under a range of dry weight as well as capital investment, operations, and maintenance scenarios. Biological research on the impact of algal growth states (i.e., biofilm vs. planktonic) on maintaining culture stability, the characterization of lipids as a function of the harvesting and/or drying technique, and the investigation of biological harvesting options was suggested. Suggested chemistry and engineering research priorities included materials, membranes and filters with a focus on fouling propensity; flocculation chemistry and the impact of chemical impurities in lipid processing; and reprocessing and recovery of flocculants.

Extraction

The goal of the extraction breakout was to solicit comments on potential barriers and targets for energy- and water-efficient extraction processes for algal lipids and byproducts. The comments were grounded in suggested physical and energy limitations of cultivating and extracting lipids in a net energy positive scheme, and a set of assumptions were used on biomass and lipid production to calculate an energy budget in the production process. Fundamentally, comments indicated that extraction processes will depend on decisions made regarding production and processing technologies, making it difficult to evaluate any given extraction process. Within this context, suggested priorities were as follows:

- Development of extraction technologies that work in the presence of water
- Development of extraction technologies resulting in solids loading of 20 percent solids
- Energy uses in extraction of no more than 10 percent of the overall energy in the final product

Fuel Conversion

The fuel conversion group provided comments on potential strategies for improving efficiencies and costs of converting fuels derived from algae, algal oils, and other algal extracts into fuels and comments suggested that leveraging both commercial and federal technological and research capabilities could be a powerful combination. Related technical and economic challenges of each algal biomass conversion technologies are described presently. Based on comments, these were broken down into the following categories:

- Production of fuels directly from algae
- Conversion of whole algae into fuels using pyrolysis, gasification, and supercritical fluids
- Conversion of extracted algal oil and other algal extractives using catalytic cracking, chemical transesterification, and biocatalysis
- Utilization of algal remnants (e.g., carbohydrates) after extraction for fuel conversion

Participants suggested that cross-cutting projects should be developed and co-processing opportunities with other biofuel targets should be pursued. Comments emphasized that discussions with regulatory agencies and fuel standards organizations need to begin, along with the development of process models and research to thoroughly characterize feedstocks that would enable the realization of algae-based fuels that are “fit for purpose”. Suggested priorities from comments included:

- Identification and evaluation of quality control and assurance protocols of algae and algal extracts during conversion
- Evaluation and testing of fuels as a function of feedstock and conversion technology
- Development and testing of performance metrics for engine performance and emissions using converted fuels
- Execution of substantial technology demonstration projects linking algae, extracts, intermediates, conversion processes and fuel products are needed

Co-Products

Comments provided in the co-product group indicated that process decisions and economic factors shape co-products market. Several different technologies were raised in the comments that are capable of producing a wide variety of co-products, including:

- Conversion of glycerol using microbial fermentation, gasification, catalysts, and enzymes
- Production of animal feeds and fertilizer
- Production of enzymes using algae
- Production of proteins, anti-oxidants, polysaccharides, polyunsaturated fatty acids, and isoprenoids
- Production of cosmetics, surfactants, and biopolymers

Comments appeared to assume a scenario where relatively low-value biofuels drive co-product production (versus high-value product production with biofuel feedstock production as an ancillary purpose). In conceptualizing this system, different co-product production scenarios were put forth: no co-products; removal of proteins, non-fuel lipids, or carbohydrates; or extraction of fuel lipids and utilization of residual biomass. Comments suggested priorities, including:

- Characterization of protein quality for feed and using genetic tools for optimizing protein synthesis
- Development of metabolic profiles and engineering tools for algae
- Development of bio-resource support services such as strain collections and data resources
- Analysis of algal biomass use as fertilizer

Policy

The policy topics include a number of non-technical but highly relevant topics for comment, including regulation, finance and public/private partnerships. Comments from the other groups indicated that commenters believed that interface between policy and science is important to consider in the development of an algal biofuels industry. Comments from industrial participants suggested that the lack of clarity regarding the roles and responsibilities of various existing federal regulatory agencies with respect to algal biofuels deployment (e.g., air emissions, water quality, genetically modified organisms, co-products such as animal feed) represents a formidable and costly challenge. Furthermore, comments stated that more work will be necessary to establish the common language needed to establish a meaningful regulatory framework. Thus, it was suggested that DOE could begin by conducting life cycle analyses and environmental impact assessments as well as information infrastructure and research, development and deployment funding.

Regulation

The scope of comments about the development of a unified regulatory framework for the algal biofuel industry focused on guiding the development of the industry. Existing regulatory jurisdictions cross multiple federal agencies, as well as state and local bodies. Contributed lessons from past biofuels initiatives included the suggestion that a commitment to lifecycle-analysis-driven sustainability targets and the proper application of performance-based incentives are crucial in developing the industry. Suggested policy priorities included:

- A strong federal effort to reduce uncertainty including loan guarantees and market and tax incentives
- Clarification of intellectual property (IP) policy in public/private partnerships
- Commitment to developing basic human and technical research infrastructure
- Commitment to lifecycle-analysis-driven sustainability considerations in policy development

Public/Private Partnerships

Public/private partnerships were recognized in comments as important and useful in developing an algal biofuel industry. The scope of the comments covered two main areas: financial risks and IP. Comments on financial considerations focused on what DOE could specifically implement to improve the financial landscape for development of an algal biofuels industry. Suggested priorities included:

- Joint long-term funding of pilot facilities
- Loan guarantees for a diverse portfolio of algal biofuel facilities
- Guaranteed offtake contracts

A point raised by comments from industry is that the engineered systems to produce algal biofuels at scale do not presently exist; consequently, private investment sources are leery of funding this effort. Exclusive IP's were recognized as particularly thorny issues which can hinder evaluations and deployment of algal production systems. In addition, comments stated that there is a general lack of established standard measures and reporting methodologies. For this reason, commenters asserted, government investment in demonstration facilities are needed to provide proof of concept and ultimately serve as a catalyst for further investment by private sources. Comments form industry participants were that such facilities could support activities such as techno-economic modeling, cyber-infrastructure generation, vehicle performance evaluation, algae and lipid characterization, protection of intellectual property, and genome sequencing, and that such a facility could help reduce the costs of raising capital.