U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Algal Biofuels Strategy

Proceedings from the
March 26–27, 2014, Workshop
Charleston, South Carolina

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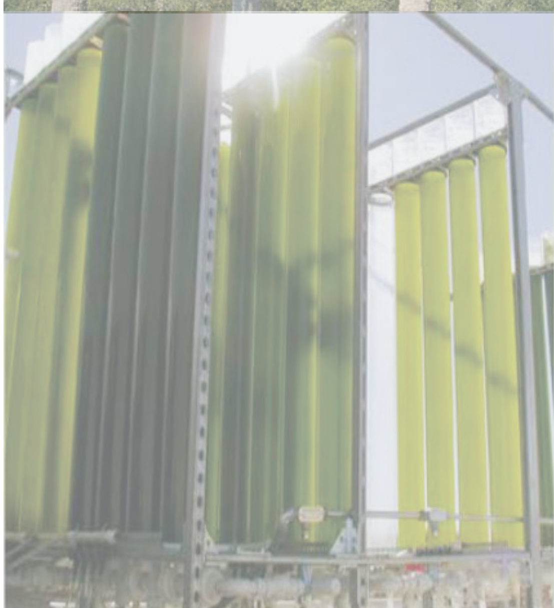

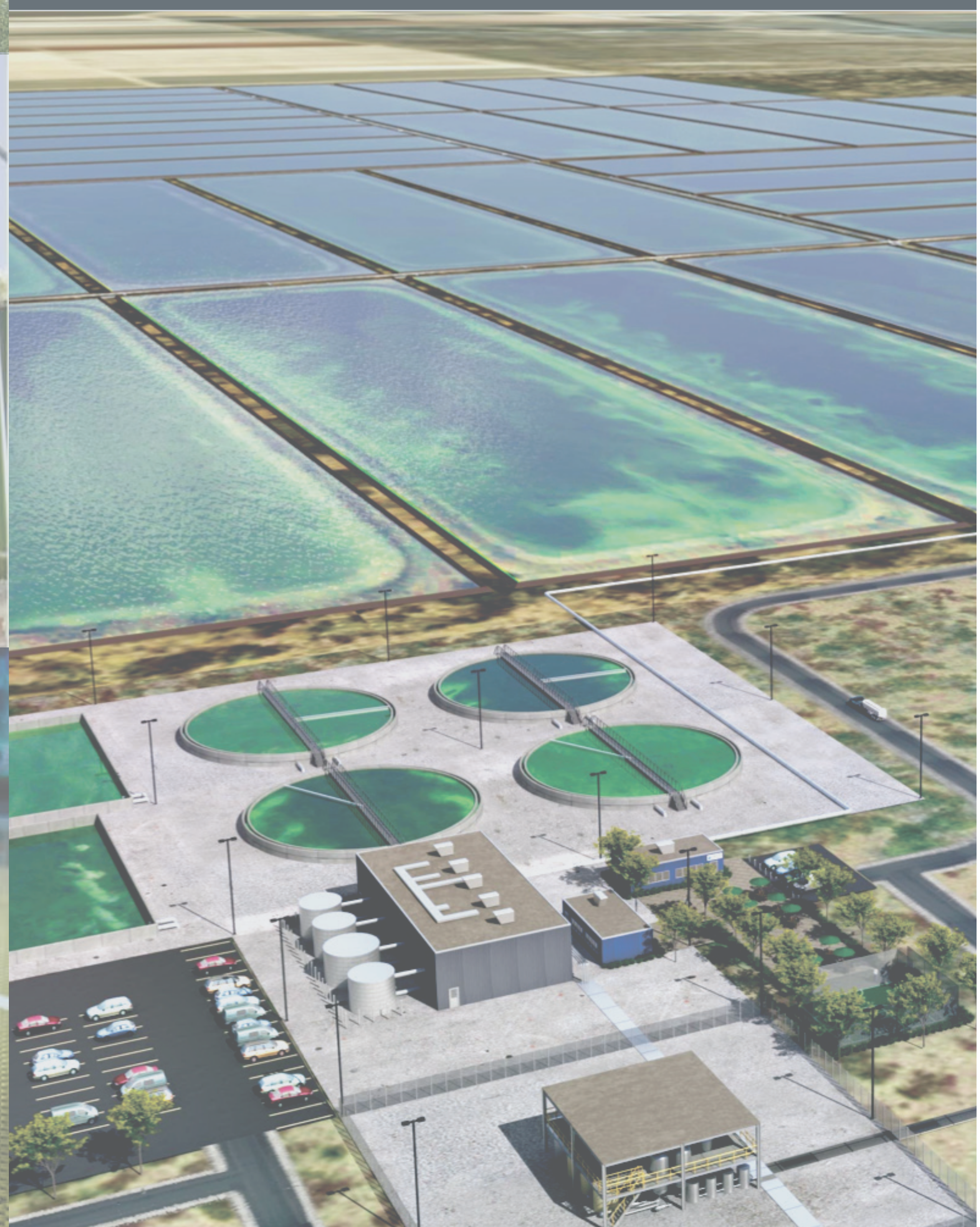

Algal Biofuels Strategy Workshop
Spring Event Proceedings

These proceedings summarized the results of a public workshop sponsored by DOE/EERE in Charleston, South Carolina, on March 26–27, 2014. The views and opinions of the workshop attendees, as summarized in this document, do not necessarily reflect those of the U.S. government.

Photos for cover provided by Sapphire Energy and Arizona State University

INTRODUCTION

The U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy's Bioenergy Technologies Office's (BETO's) Algae Program hosted an algal biofuel strategy workshop on March 26–27, 2014, in Charleston, South Carolina. The workshop objective was to convene stakeholders to engage in discussion on strategies over the next 5 to 10 years to achieve affordable, scalable, and sustainable algal biofuels. Approximately 125 university, national laboratory, industry, advocacy, and government stakeholders participated in the event.

Bioenergy Technologies Office Algae Program

An overarching strategic goal of the Office is to develop sustainable, commercially viable biomass technologies that enable a domestic bioenergy economy, reducing America's dependence on foreign oil, and reducing greenhouse gas emissions. Biofuel intermediate feedstocks derived from algal biomass can contribute significantly to expanding the domestic, advanced biofuel resource potential. This contribution is based on the potential for the high productivity of algae while using non-arable land, brackish water, or salt water, and on the possibility of using waste nutrients and effluents. The ability of algae to accumulate significant amounts of lipids makes it particularly well suited for conversion to hydrocarbon-based fuels, such as renewable diesel and jet.

The Algae Program focuses on overcoming technical barriers to the cost-effective production of algal biomass and intermediates, as well as on developing logistics systems for producing commercially viable algae-based biofuels and bioproducts. Developing algal feedstocks to achieve advanced biofuel goals requires breakthroughs along the entire algal biomass value chain. The Algae Program focuses on demonstrating progress toward achieving high-yield, low-cost, environmentally sustainable algal biomass production and logistics systems that produce biofuel intermediate feedstocks that are well suited for conversion to fuels and other valuable products. The performance goal for the Program is to demonstrate technologies to produce sustainable algal biofuel intermediate feedstocks that perform reliably in conversion processes to yield renewable diesel, jet, and gasoline fuels in support of BETO's $3 per gasoline gallon equivalent (GGE) advanced biofuels goal by 2022. The Algae Program funds national laboratories, universities, industry, consortia, and a variety of state and regional partners to perform strategic research and development (R&D) activities and achieve this goal.

Workshop Process

The Algae Program kicked off the workshop by presenting DOE's aggressive algal biofuel goals and strategies and hosting a panel discussion on the Program's two algae technology pathways. Next, stakeholders were provided the opportunity to take four minutes to present their own strategies and goals in a rapid-fire format called the Open Forum Discovery Session (see Appendix B, Open Forum Discovery Session Agenda). The workshop then self-divided into five Breakout Sessions tracks, each co-chaired by two subject matter experts. The five tracks were Biology; Cultivation; Processing; Scaling and Integration; and Analysis and Sustainability. The Breakout Sessions spanned two days, focusing first on "State of the Art," with discussion questions on breakthroughs and accomplishments, lessons learned, and critical focus areas, and subsequently on "Outlook," with discussion questions on barriers and next steps. (See Appendix A, Workshop Agenda).

Workshop Outcomes

Discussions in the Breakout Session tracks converged towards common outcomes. The emergent theme was the need for integration of all technology areas in the supply chain in a cross-disciplinary manner. Key messages from these discussions included the following:

- DOE catalyzed an impressive array of algal biofuel technology developments over the last 5 years, and should continue to lead an aggressive implementation of a 10-year strategy for algae
- DOE strategies could be improved through advanced planning, more focused execution, and enhanced collaboration
- Improving biomass yields is a critical barrier for R&D to address
- Developing bioproducts as a way to build infrastructure to enable biofuels is critical and timely.

Responses to the discussion questions posed by the Breakout Session co-chairs are briefly summarized below.

Breakthroughs and Accomplishments

Significant recent breakthroughs listed by participants ranged from specific genetic tools to operation of multi-acre algal biofuel facilities. It was repeatedly noted that with comparatively (to traditional biofuel development) limited investment, technology for algal biofuels has greatly advanced in the past 5 years and that the algal biofuel value proposition and remaining challenges are much more clearly understood. Notable accomplishments include successful large-scale crop protection techniques, genetic transformation techniques, development of data and methodological infrastructure required for replicable and robust field trials, the beginnings of process integration, and a range of downstream fuel certifications and demonstrations. The development of hydrothermal liquefaction (HTL) for algal biofuel production was repeatedly identified as a prominent enabling accomplishment. With greater than 50% carbon conversion efficiency to fuel, HTL broadens the types of algae that can be grown by potentially diminishing the need to cultivate high-lipid content algae. Polycultures and attached growth algae turfs were discussed as now showing potential for biofuel production in light of the HTL efficiency. Polycultures could result in lower cultivation capital and operating costs through strategies utilizing mutually beneficial interactions among different strains to boost algal productivity and yield.

Lessons Learned:

The problems related to scaling results produced in laboratory settings to relevant and reproducible field trial scales emerged as an overarching theme. For example, the Biology Track identified the process of scaling valuable traits from a laboratory environment to production scale as a challenge because of the many unknown variables that affect productivity measures and strain robustness. In addition, operational considerations with respect to culture media and the availability or scarcity of nutrients was an important lesson learned. Other notable lessons learned include knowledge continuity to ensure culture collections and experience are not lost and the need to focus on sustainable resource use.

Critical Focus Areas:

Several critical focus areas were identified. For example, there is a need to bridge the lab to production scale gap through application of robust laboratory techniques capable of predicting relevant outdoor conditions. In the cultivation section, the focus was on the use of obtaining lab data that is relevant and is able to inform production at scale. Analysis and sustainability sections discussed the need for more field data by which to develop models that enable the extrapolation and validation of data-to-production scales. Other important critical focus areas include the need for integrated modeling (life-cycle analysis, technoeconomic analysis, resource assessment, and economic impact) that is publicly available with transparent documentation for data. Standardization and improved technical communication were noted as requirements across the sessions. In addition, cost-related issues were a high priority for many breakout groups; scaling and integration highlighted the clear requirement for lowering capital and operating expenditures (CAPEX and OPEX) to drive down costs, though an accompanying barrier was the lack of consensus on how to measure and report CAPEX and OPEX in a consistent and transparent method. An emergent issue is how to translate complex operations to “farmer-ready” production environments.

Next Steps:

Key next steps not mentioned above include the following:

- DOE should continue to support bridging the lab-to-production scale gap; this is a complex problem requiring systems thinking and analysis.
- Improving biomass yields is a critical barrier for R&D to address.
- Research progress for biology improvements, cultivation, and nutrient capture and reuse continue to be high-impact areas.
- Integration between upstream and downstream technologies is critical for meaningful progress.
- Regulatory guidance on deployment of genetically engineered strains; use of flue gas carbon dioxide (CO_2); fuel production and certification; and the Renewable Fuel Standard (RFS) will have major impacts on the development of algal biofuels.

Algae Program staff participated in the breakout sessions and received valuable input on these and many other issues from the Algal Biofuels Strategy Workshop attendees. Breakout session co-chairs provided DOE with more detailed discussion summaries, organized by track in the subsequent chapters of these proceedings.

PROCEEDINGS: BIOLOGY

Focus Question 1: Breakthroughs and Accomplishments

- Downstream processing technologies have made it feasible to use any biomass to make fuel, reducing the dependency on lipid production.
  - This observation has been corroborated both by academic and industrial groups.
  - The implications are a broad range of lipid:carbohydrate ratios in algal biomass yield biocrude products of similar energy content and only slightly different chemical composition.
  - Given that starch synthesis and accumulation is thermodynamically and kinetically more efficient than oil production, there may be less of a need to focus on oil production; instead, the goal could be biomass accumulation. (Some participants cautioned that we have insufficient knowledge of the complexities of hydrothermal processing of algal biomass.)
- Development of molecular technologies
  - This includes molecular toolboxes for strain improvement and development of advanced genomics, transcriptomics, proteomics, metabolomics, and phenomics platforms.
  - In the past decade, rapid advances have been made in molecular biology tools that allow scientists to manipulate algal genomes to express new or altered proteins, including those involved in metabolism and photosynthesis.
    - At the same time, the development of ‘omics tools has enabled researchers to characterize the algal biological system with orders of magnitude more information.
    - Together, these technologies have the potential to transform algal biotechnology.
    - Session participants noted that the integration of these ‘omics technology platforms is lagging and should be advanced using samples from a single preparation or culture.
- Recognition that algal strain robustness is critical for large-scale cultivation
  - Numerous observations by the algal research community indicate that laboratory performance characteristics may change when scaled up to outdoor, open ponds and to other systems that expose cells to highly variable environments.
  - This is not surprising, since evolutionary selection would select for traits that maximize survivability and reproduction in a broad range of environments; Recent efforts toward commercialization have provided evidence for those hypotheses.
- Development of directed evolution and high-throughput selection systems for development of superior algal strains.
  - This point follows directly from the statements above. Directed evolution studies tend to be less gene-specific in their application and outcomes and can lead to better understanding of the integration of metabolic networks.
  - These types of studies need to be encouraged since they complement specific synthetic biology approaches.
- Recognition of the need to control algal pathogens
  - With the increasing number of larger-scale, outdoor cultivations has come the recognition that rotifer invasions present one of the greatest threats for pond crashes. Novel, safe, and effective strategies need to be developed to control rotifers.
  - Additionally, integrated pest management systems need to be developed to control pathogens and herbivores.

Focus Question 2: Lessons Learned

- Recognition that energy return on investment (EROI) and carbon index are central to the success of algal biofuel production.
    - Substantial progress has been made in the performance characteristics of algal fuel systems ranging from biology to end products used by the consumer.
    - However, further work is needed using a combination of the best-of-the-best technologies bench marked against baseline old technologies to assess the improvements that have been made on EROI and carbon index.
- Generalization of "algae" is problematic because of the enormous diversity.
    - The algal biotechnology community has realized to a much greater extent that the algae are a very diverse group of organisms coming from multiple eukaryotic phyla as well as bacteria.
    - This range of diversity and immensity of potential genetic resources and tools has been barely characterized.
    - Given the advances in single-cell and high-throughput genomics, it is now possible to bio-prospect the algal genomes of entire lakes, rivers, and potentially, oceans.
- Scaling from lab to production is challenging.
    - The community has learned that using laboratory culture data leads to poor prediction of large-scale cultivation performance.
    - There are multiple platforms being used to assess laboratory, greenhouse, and outdoor production systems.
    - Unfortunately, there is a range of performance characteristics observed between different bench scales and larger-scale outdoor systems. It is now recognized that lab-scale photobioreactors and enclosed/greenhouse systems can be designed to meet or exceed outdoor performance traits.
    - Other aspects of this challenge include the complexities presented by the ecology of larger-scale systems (undesired algal and bacterial species) and the fact that some species appear to be less well suited to large-scale cultivation.
    - Finally, the community has learned that practical knowledge of growing algae is critical.
- Standardized methods are critical.
    - Another lesson learned from the many efforts to scale up and quantify algal cultivations is that there is no standard set of performance characteristics to describe algal production systems.
    - Given the constraints that photosynthesis is a quantum-driven process and that the photon flux on the surface is an operational constraint, there is a growing recognition that all yield performance traits should be based on areal measurements of photon flux.
    - Similarly, algal yields should always be expressed on areal productivity as well as other measurements of productivity (e.g., volumetric productivity).
    - In addition, growth temperatures, medium composition, aeration, pH control, and reactor design and dimensions need to be noted for comparative purposes.
    - Finally, biochemical fractionation and quantification procedures need to be standardized as much as possible.
- Other suggestions of lessons learned by the community include the following:
    - Industry recognition that producing non-fuel products is an important transition step to commercial production of algal biofuels
    - Commercialization must consider the regulatory arena
    - There is a strong need for well-trained bioinformaticists
    - Algal biology efforts must be compatible with downstream processes, including harvest
    - There is a need for greater integration of life cycle analysis (LCA)/ technoeconomic analysis (TEA) analyses in projects.

Focus Question 3: Critical Focus Areas

- Yield, yield, yield (and productivity)
  - Since the biochemical makeup of algae, i.e., lipid:starch:protein ratio, is less important for fuel conversion than previously recognized, it is apparent that the major constraint facing commercial development of algal biofuels is total biomass yield.
- Domestication of algae, including transmission genetics, and molecular modifications for strain development
  - The terrestrial crop industry has benefitted enormously by using traditional breeding technologies, e.g., recombinant inbred hybrids to substantially increase yields over the last 50 years.
  - Virtually nothing is known about transmission genetics in microalgae or how to identify and induce mating competency in a given species. Yet we find genes for meiosis and mating types in diploid algae that have not yet been segregated into separate mating types.
  - Once classical breeding systems are developed for diploid algae, we will be able to take advantage of the tremendous gene diversity for species from diverse environments and utilize the power of marker-assisted selection, TILLING, and mapping of quantitative trait loci to breed for better performance characteristics.
- Development of metabolic engineering/synthetic biology platforms for photosynthetic organisms
  - One of the challenges facing the development of transgenics in algae is the expression of multiple genes in a single transformation event or expressing entire metabolic pathways.
  - There needs to be the development of molecular tools such as the 2A system for expressing polycistronic elements or CRISPR/kas or TALEN systems to do targeted gene replacements.
  - In addition, the use of synthetic biology approaches to create algal strains with desired properties would benefit from a "chassis" with a simplified, well-characterized genome.
  - Finally, the development of platforms for channeling metabolic pathways to reduce diffusional limitations is needed. The sequencing and annotation of more algal genomes would provide essential biological data to support these efforts.
- Development of better models for lab-to-commercial scale
  - As stated in one of the lessons learned, there is a need to develop better experimental and computational approaches to use laboratory data to accurately predict commercial-scale performance.
  - Part of this challenge is that there is not yet enough experience with large-scale production.
  - Currently, federal funding is focused on projects ranging from basic/exploratory research to the development of small-scale pilot plants. There is a lack of capital to take successful pilot plant systems to commercial scale ($500 million–$1 billion).
- Development of the following additional molecular tools, which are desperately needed by the algal biology community:
  - Robust homologous recombination systems
  - Gene switch technologies
  - Remote sensing
  - Feedback control systems to control metabolism in real time.
- Biocontainment systems for transgenic algae.

Additional focus areas suggested by the community are the following:

- Increased availability of biomass to encourage valorization of algae
- Obtaining regulatory clarity
- Improving public perception of genetically modified (GM) algae
- Development of approaches for algal crop protection
- Development of stable, productive polycultures (engineered or natural).

Focus Question 4: Barriers

- Lack of an integrated and stable funding plan for algal research and development
  - Representatives from academia, the national laboratories, and industry all identified the lack of a detailed, coordinated roadmap for R&D as a significant barrier.
  - The National Algal Biofuel Technology Roadmap[1] has provided value, but participants commented that it was very broad, lacked specific milestones, and needs to be updated to reflect the significant progress that has occurred in the past few years.
  - A very important point is that funding across the spectrum—from basic research grants to support for commercialization—must be at a significant, consistent level and must be tied to the strategies in the roadmap.
  - The variable levels of funding in recent years and uncertainty about future funding levels was unanimously cited as one of the top barriers to the attainment of DOE's goals for algal biofuels.
- Communication barriers between basic research and applied groups and poor alignment of objectives
  - For a variety of reasons, basic research at universities and the national labs has, in many cases, proceeded in parallel with applied research and development in private industry.
  - While basic research results are published, those from industry are rarely made available to others.
  - While industry can fund and conduct projects more rapidly than basic researchers who are subject to the lengthy proposal review cycles, industry projects must drive rapidly toward practical targets and may overlook important basic research questions.
  - To more rapidly achieve DOE goals, and to better use limited financial resources, the two communities should interact more and share data (to some degree). Without this cooperation, basic researchers often repeat work already done in companies.
- Failure to communicate compelling arguments that recognize and promote the advantages of algal biofuels
  - Participants commented that a barrier to public (and legislative) support for algal biofuels has been our community's failure to adequately provide strong messages about the potential benefits of producing fuels and other products from algae.
  - Messages about carbon capture, wastewater treatment, protein production, and lack of competition for prime agricultural lands would help DOE, researchers, and companies obtain more funding and would help to reduce regulatory and other policy barriers facing the algae industry.
  - Given these concerns, it is recommended that the National Alliance for Advanced Biofuels and Bioproducts (NAABB) final report be made publically available as soon as possible and that the results and conclusions from this report be widely disseminated, not only to academic, industrial, and government agencies, but to the public as well.
- Lack of government inter-agency coordination
  - R&D efforts related to algal biofuels have been supported by several programs within DOE, as well as some of the U.S. Department of Defense research offices.
  - In addition, the National Science Foundation has supported basic research on algal biology and biotechnology, and the U.S. Environmental Protection Agency (EPA) has jurisdiction on many of the regulations that impact commercial algae production.
  - The session participants stated that the lack of coordination among these programs (even within the same agency) has been an impediment to the development of the field.

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[1] DOE 2010. National Algal Biofuels Technology Roadmap. U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Biomass Program. bioenergy.energy.gov/pdfs/algal_biofuels_roadmap.pdf

- Furthermore, participants strongly recommended that other agencies join in this coordinated effort to develop algae-derived biofuels and other products. For example, the U.S. Department of Agriculture (USDA) should view algae as a crop and provide support as it does for crops such as corn and wheat.

- Lack of genomic and bio-informatics tools and data
  - While there have been many advances in genomic and post-genomic tools and databases in the past five years, the ability of algae researchers to use approaches from systems and synthetic biology is far more limited than for our colleagues working in the biomedical sciences.

Additional barriers noted by the community are the following:

- Most investigations are focused on a small set of algal strains, and we are not benefitting from the traits of unstudied species.
- There are seasonal constraints on productivity in many regions.
- Successful commercialization means that companies need support to cross the "valley of death."
- Algae does not have policy parity with other biofuel feedstocks.

Focus Question 5: Next Steps

- Develop a 10-year R&D plan with a detailed set of objectives and milestones.
  - Session participants unanimously supported developing this plan as a top priority since they identified the lack of an updated roadmap as one of the top barriers.
  - The plan should be developed with input from a wide range of stakeholders including NAABB leadership, and funding programs should be coordinated with this plan.
  - Since R&D outcomes are difficult to predict, a regular mechanism for updating the plan should be considered.
- Express a coordinated vision for the future of algal biofuels production that recognizes its unique contribution to sustainable energy and green feedstock production as well as its unique potential to promote environmental sustainability.
  - Session participants said this was an obvious next step to correct the lack of a clear message about the benefits of algal biotechnology.
  - Representatives from industry, government agencies, and universities could work together to create broad public awareness of the potential for algal biotechnology to provide important products—fuels and many others—in a sustainable manner.
- Address water and nutrient conservation issues and set rational targets.
  - The large-scale cultivation of algae will require significant inputs of water and nutrients (nitrogen, phosphorus, and others), and a considerable effort is needed to develop strategies for minimizing the use of those resources while maintaining the ability to produce cost-competitive products.
  - A related action is to determine reasonable targets for nutrient and water use so that the resources for large-scale cultivation facilities can be properly designed and sited.
- Develop a range of commercially relevant model organisms that reflect the evolutionary diversity of algae.
  - The algae (including cyanobacteria) are an extraordinarily diverse group of organisms, but the power of this diversity has scarcely been used.
  - While more rapid development of an algal biotechnology industry can benefit by focusing on a relatively small number of organisms, this development must be balanced with strategies to select model organisms that represent the available diversity while maximizing yield.

- Invest in synthetic biology platforms and tools.
    - Most of the session participants said that synthetic biology approaches for algae and cyanobacteria are critical for achieving DOE program goals and should be supported to a larger extent.
    - Synthetic biology refers to the modification of the metabolic pathways and regulation of cellular functions. Example applications include the introduction of new pathways (as in the photosynthetic production of ethanol or sucrose by cyanobacteria), replacement of specific enzymes with optimized variants, and replacement of promoters to optimize gene expression.
    - Tools to accomplish these goals are well developed for organisms of interest to biomedical researchers but are far less developed for algae and cyanobacteria, even in the most studied alga, *Chlamydomonas reinhardtii*.
- Develop genetically modified organism (GMO) and safety strategy, policy, and guidelines.
    - In parallel with investment in tools and database for the genetic modification of algae, the session participants recommend the development of clear, coordinated, and rational strategies, policies, and guidelines for the use of GMO algae.
    - In most cases, current policies and regulations are very outdated and do not recognize current genetic methods and future deployment scenarios.
    - Those involved in the research, development, and commercialization of GMO algae should work with federal, state, and local regulators to develop responsible solutions. In many cases, the knowledge of phycologists, molecular biologists and ecologists may prove useful in finding novel solutions that prevent undesired outcomes.

PROCEEDINGS: CULTIVATION

Focus Question 1: Breakthroughs and Accomplishments

The discussion focused on accomplishments in the last several years specific to the cultivation of algae as well as the role of cultivation within the broader context of an integrated algae production process.

- General accomplishments: Demonstrated lipid production greater than 2,500 gallons/acre/year (Cornell Consortia)
- Applied algal molecular biology accomplishments:
  - GMO technology dramatically advanced
  - ‘Omics data being applied.

As GMO technologies have advanced over the last several years, an emphasis has been placed on how those advancements will be deployed to commercial production. Application of TSCA to non-food GMO microalgae via the U.S. Environmental Protection Agency (EPA) was discussed.

The discussion proceeded with the following:

- Polycultures: Dynamic polyculture concepts have emerged and have value at scale
  - The majority of prior work in algal biofuels production has focused on monocultures; recent work has shown increased robustness of polycultures, and the utilization of technologies including hydrothermal liquefaction (HTL) that are effective at producing biofuel from a broad range of organisms makes utilization of polycultures feasible.
- Physical systems: Multiple diverse systems have reached acre-scale for biofuels production
  - Discussion centered on a number of technologies, including algae turf scrubbers, solid-phase rather than liquid-phase photobioreactors (PBRs), and the potential use of open-ocean floating PBRs for algal production.
  - The application of computational fluid dynamics for system modeling prior to construction was discussed, and it was pointed out that multi-acre raceway systems for biofuel production have come on line.
- Nutrients and physiology: De-emphasis of N starvation, focus on efficient nutrient use
  - The utilization of nitrogen starvation for induction of triacylglycerol accumulation has been a longstanding focus of microalgal biofuel production. With new technologies, including HTL coming online, efficient fuel production may not require N starvation. While cultivation of nutrient-replete systems for fuel production may be feasible, a focus on efficient nitrogen use and accurate mass balances was emphasized.
- Process development: Development of feed forward controls and automation improving systems
  - Significant breakthroughs in process understanding and automation have occurred in the last several years, allowing increased process efficiency and feed-forward control schemes in some instances.

Focus Question 2: Lessons Learned

- Experience counts; need to involve the farmers
  - Practicing algae farmers have not been adequately invited, engaged, or involved in technology and process development. Their considerable experience should be recognized and more actively engaged.
- Communications—its importance as an overarching principle
  - Public relations (PR), especially around GMOs, will be challenging
  - Despite PR challenges, this direction of R&D should be pursued, at the very least to build knowledge and understanding.
- Economic realities: cost matters, capital costs remain high
  - Algae cultivation systems are inherently capital intensive, but costs are continuing to come down, especially for pond technology, which has now been sustainably demonstrated at large scale (1 hectare) at many locations.

  - PBR systems continue to be more costly than ponds, but they will play a role at some scale in every cultivation process; PBR cost effectiveness can be significantly optimized.
  - Harvesting system costs remain unacceptably high for all but a few strains with special characteristics.
- Impact of regulations and funding—don't rely on tax credits or subsidies
  - Regulatory requirements can have a significant impact on economics and should be carefully considered from that perspective on this young industry.
  - There was a widespread plea for more funding, noting by contrast, the relative resources dedicated to cellulosic ethanol.
  - Regarding reliance on tax credits or subsidies, several examples of other renewable industries were noted as not especially encouraging.
- Scaling realities: CO_2 and phosphate supplies not as large
  - Large point-sources of CO_2 are costly to access. Most are in developed areas, far from areas suitable for large-scale algae cultivation. Most sources are also of low purity. Both factors increase the cost of pipelines beyond affordability for most cultivation sites.
  - Alternate sources and methods of CO_2 supply are needed for algae cultivation to be more than a cottage industry. Global phosphate supplies are expected to soon limit agricultural production, and will have a strong effect on algae cultivation.
  - Processes for recycling phosphorus in algae cultivation systems have not been well explored or demonstrated. Viable processes for recycling phosphorus could set algae apart from other bioenergy crops.
- Flask vs. field: the distinction is important
  - Large-scale cultivation is costly and, because of the scale, the ability to experimentally manipulate culture conditions is limited.
  - Small-scale cultivation allows greater scope for experimental manipulation but, because of the scale, applicability of the results to large scale may be questionable.
  - We do not have a good quantitative understanding of how performance at small scale reliably predicts performance at large scale.
  - The ability to predict large-scale results could rapidly accelerate development of advanced strains and improved culture management practices.
- Knowledge continuity: Much that was learned or isolated during the Aquatic Species Program has been lost or has been ignored
  - This observation was not so much a lament of the past as an admonition that this lesson, having now been learned, should not be repeated.
- Process lessons—intrinsic kinetics! = process kinetics
  - Many advances in process development have now shown us that the intrinsic kinetics of biological or biochemical processes are useful guides for process engineering.

Focus Question 3: Critical Focus Areas

- Biology
  - Strain selection including attached, macro, etc.
    - Significant improvements in strain performance are to be expected, comparable to or better than those achieved in terrestrial crops.
    - Taxonomic and habitat diversity should be expanded to include more macrophytes, which may be as productive as microalgae and are much easier to harvest.

    - Data modeling– more ‘omics and lab data that are relevant to production
    - Consortia– emergent and designed ecologies
        - Groups or consortia of organisms in designed ecosystems may yield more stable cultivation conditions or enable improved performance.
- Cultivation systems
    - Equipment development
        - *Unit operation designs, reactor design*: Capital cost effectiveness of photobioreactors remains challenging, and little direct comparison of alternate PBR designs has been done. More innovative approaches are needed to reduce the energy costs of recirculation in both PBRs and ponds, which can have a significant GHG impact.
        - *Control systems*: Control systems have not been widely demonstrated in large-scale algae cultivation, where they are essential to improving culture management. The algae industry can take advantage of significant advances in sensor miniaturization and distributed communications to develop process-control systems that are fit-for-purpose for algae cultivation.
        - *Open water systems*: Open water systems have the clear and significant advantage of not requiring land. This category of systems—which may include both open and closed systems and which could apply to either macroalgae or microalgae—has not been well developed. Innovative engineering in open systems is needed to make breakthroughs in economic and/or life-cycle assessments.
        - *Durable, low cost systems*: There is a continuing call for reliable, low-energy, low-cost cultivation systems that can be swiftly deployed and brought into operation.
- Process development
    - Cost effective processes
        - *Inoculum production*: Reliable inoculum production is required at some scale in all cultivation systems except for those that exploit ambient species assemblages. This means, generally, the use of photobioreactors at some scale. The answer to the question, “Which scale, if any, is most cost-effective?” depends to some degree on the cultivation process, but nevertheless, is not well demonstrated.
        - *Simple systems with low energy input*: Energy demand for cultivation is dominated by the need for recirculation of cultures and for fluid transfers that take place in the entire cultivation process. Are there any processes more efficient than a pond paddlewheel?
    - Focus on resource efficiency and sustainability including CO_2 supply
        - The viability of freshwater vs. saltwater systems is site dependent, but there is recognition that saltwater volumes may be more available and more sustainable. Alternate sources of CO_2 need to be explored as the technologies now being considered are costly and have limited application.

Focus Question 4: Barriers

- Policy and funding engines (lack thereof)
    - Incentives
        - The group once again acknowledged the uncertain availability of policy-driven incentives such as tax credits, subsidies, and loan programs, and issued a plea for more sustained and reliable policies.
    - Ineffective promotion of funding opportunities
        - There is a concern that funding opportunities are not actively disseminated or made widely known and thus many potential advances and innovations could be missed.

- Information availability
  - Public data
    - All funded projects could make a significant contribution to publically available data, and the DOE could do more to ensure the establishment and maintenance of those databases.
  - IP protection
    - More clarity from the DOE on standards of IP protection could be a factor in the willingness to share proprietary information.
  - Unified/standardized data across scale
    - DOE has the opportunity to take a lead role in creating a standardized community database that could rapidly accelerate process development.
  - Translating performance
    - More information on the correlation of performance at small and large scales is needed.
- Cultivation challenges
  - Management techniques at scale
    - As made evident by analogy in large-scale agriculture, great improvements in yield can be achieved by managing simple culture conditions such the type, timing, and intensity of fertilization, or hydrodynamic conditions that favor or inhibit gas exchange, all of which influence productivity.
    - In algae cultures, such conditions change on the time scale of hours, so management techniques that operate at this time scale are essential.
  - Efficient resource utilization
    - More demonstrations are needed that accurately quantify key resource use efficiencies for water, energy, and nutrients, including CO_2.
- Human capital
  - Limited experience and industry participation
    - Large-scale algae production is a new field of bioprocess engineering in which few people are sufficiently educated or experienced across disciplines.
    - There are, for example, many qualified aquatic biologists and many qualified engineers, but few have worked together or sufficiently understand the suite of practical issues arising at the confluence of biology and engineering.
    - More could be done with the collaboration of universities, DOE, and the private sector to enhance the skills and abilities of human resources.
- Lack of an organized approach
  - Integrated multi-disciplinary strategies
    - Projects should be encouraged to engage in the innovation that can occur at the interface of well-managed inter-disciplinary activities.
    - The emphasis here is on addressing the organizational process, assuming that the appropriate mix of disciplines is in place.
- Industry Involvement
  - There is a general sense that industry has shared only very limited information from its recent significant experience and that, as a result, other members of the broader R&D community are unable to build upon that experience.
  - Whatever the case may be, any programs that encourage industry to collaborate more with universities and federal agencies would be of great value.

Focus Question 5: Next Steps

- Policy and funding engines
  - Update and clarify roadmap, streamline funding process.
- Information availability
  - Expand test bed program to long term and large scale, reduce pressure on test beds to be "businesses."
  - Leverage DOE assets like the Joint Genome Institute to disseminate data.
- Cultivation challenges
  - Development of "farmer friendly" pond diagnostics systems
  - Improved availability of 'omics
- Human capital
  - Development and deployment of training programs
- Lack of an organized approach
  - Focus funding on cross-category efforts and development of moderate value products
- Industry involvement
- Cross-fertilization at industry conferences, expand collaborations between DOE and USDA, EPA to address cross-department issues.

PROCEEDINGS: PROCESSING AND CONVERSION

Focus Question 1: Breakthroughs and Accomplishments

- Integrated Processes
  - Using nutrient-rich impaired water (and/or wastewater) streams
  - Small companies with smaller-scale (local) process and product portfolios that can be economically viable.
- Baseline-case technoeconomic and life cycle analysis have been completed and provide processes to compare to extraction advances—wet processes (Valicor and Inventure), and multiple product streams
- HTL—initial continuous processing and carbon recovery
- Filtration advances
- Progress toward green and sustainable processing
- Algal oil has been converted to jet and biodiesel and the resulting fuels meet American Society for Testing and Materials standards.

Focus Question 2: Lessons Learned

- Make sure to do calculations to understand economics, effectiveness, mass and energy balances, etc., prior to scale up.
  - Coproducts are still an important part for economics and process development.
  - There are diminishing incentives for working with other industries and agencies.
  - Understanding the effects of co-location of CO_2, water, and land (for processing) is key.
  - Precompetitive information needs to be easily shared without compromising IP; for example, strategies to use impaired waters or to avoid pond contamination.
- Algal oil processing is not the same as vegetable oil processing (more water in algal oil processing); hence, more research is required with algal oils and not surrogates.
- Need data standardization for the following:
  - Quality of oil (lipid or HTL); for example, amount of nitrogen that needs to be reduced prior to selling to a company such as UOP.
  - The amount of water that needs to be removed prior to extraction or conversion
  - The "wet biomass standard"
- Dewatering technology is a major design factor; scalability, CAPEX, and OPEX, are all influenced by the specific process design and biomass
  - Dewatering at the pond to minimize water transport has good impact
  - Technologies need to be tested at scale (at least 100 L/min or more)
- Wet extraction is essential
  - Transport of wet biomass is challenging; difficult to avoid spoilage
  - Solventless extraction techniques are promising at the bench scale
- HTL—This technology holds promise, but there is more work to do: energy minimization, scale up, oil quality, process integration
- Process integration has to be done in a "holistic" way because of biomass variability and upstream effects on downstream processes; upstream and downstream industries and researchers must work together.
- There are probably good technology solutions dispersed among many companies; need to get information out to interested parties about advances made after allowing for IP issues.

Focus Question 3: Critical Focus Areas

- Set up an information exchange network to solve problems faster through an organization similar to the Algae Biomass Organization (ABO).
    - Published best practices; starting point is ATP3 methods but need a broader emphasis
    - Integration between groups (cultivation/processing/modeling)
- Incentivize and take advantage of "carbon tax" benefits
- Definition of standard for biocrude
    - What pieces of information are needed (define compositions N, O, and other heteroatoms, and inorganic amounts that are acceptable as petrochemical feedstocks)
    - Once the "biocrude standard" is defined, a standard method to reliably validate biocrude quality for petrochem uses needs to be developed/defined.
- Economics—more work to do
    - Credit for subsidies, health and safety; true comparisons to other industries
    - Harmonization
- Understand and develop solid/liquid separations that are both mass and energy efficient and economically viable
    - Lack of fundamental thermochemical information on algal biomass and lipids
    - Lack of thermophysical models for algal systems
- Wet extraction optimization—clearly identify trade-offs between energy, yield, and mass balance efficiency, e.g., is 75% recovery of all lipids the sole target?
    - Help with solvent development and selection
    - Development of green solvents
- Continue to evaluate integrated extraction/conversion processes, such as optimization of HTL, but continue to be open to other process ideas
- Process design data and heuristics to facilitate recycle streams and heat integration between systems
- Materials of construction
- Catalyst development for conversion of high nitrogen-containing feedstocks to fuel.

Focus Question 4: Barriers

- How to get novel ideas into the general community without subverting IP concerns?
- Wet biomass transport and/or storage needs to be avoided
- Variability of biomass and polycultures
- Valorization and recovery of all algal components, beyond lipids
- No "off the shelf equipment" exists for this industry (pharmaceutical and oil equipment not quite right).

Focus Question 5: Next Steps

- Overarching advice
  - Publication of best practices cooperative with DOE, ABO, and other third party
  - Fund smaller TR-1 projects without cost share that are pre-competitive research
- Define standards and metrics for analysis and product(s) quality checks (QC)
- Dedicated solvent research data that is relevant and in the public domain
- Process Integration
  - Predictive modeling between upstream biomass QC and downstream process design
  - Enable devices and methods for better energy integration
  - Recovery methods for all components of the algae in quality form
    - By-product utilization (QC and process methods)
- Sustainable, compact, “pond-scale” units for on-site dewatering, extraction, and other processing
- Continue to do research or have funding opportunities to address the critical focus areas stated above.

PROCEEDINGS: SCALING AND INTEGRATION

Focus Question 1: Breakthroughs and Accomplishments

- Increase in biomass production through large-scale cultivation
  - Crop protection in open ponds
  - Scalable PBR and hybrid approaches
- Large-scale growth of algae directly utilizing waste industrial CO_2
- Demonstrated product value potential
  - Co-products (poultry feed, finfish/shellfish, etc.)
  - Offtakes (Tesoro, Neste, Philips 66, HECO, etc.)
  - Drop-in fuel performance (aviation test flights, cross country car trip)
- Innovation in downstream technologies (e.g., HTL, wet solvent extraction).

Other ideas that were raised but given lower priority by the group

- Dewatering improvements at reasonable scale
- Fuel certification
- Lower-cost, scalable pond design
- Modelling efforts allowing for integrated optimization (rather than for individual unit operations).

Focus Question 2: Lessons Learned

- Demonstrating at large and fully integrated scale is essential to real world understanding of commercial systems.
- DOE plays an important role in commercial development.
- Challenge industry dogma (e.g., N starvation is needed, dissolved air flotation can't work, ponds can't be stable, GMO is necessary, auto-inhibitors are a hurdle, etc.)
- If it doesn't make money, it's not going to get funded privately.
  - To operate a business and to build an industry, one has to generate profits at small, medium, and large scale.
- There is a need to find ways to disseminate success publically as an industry without jeopardizing intellectual property.

Other ideas that were raised but given lower priority by the group

- Need to identify adjacent industry analogs
- Don't over promise and under deliver
- Must grow outside to incorporate actual regional and environmental conditions
- Whole system data collection must be considered in project plan
- On-site integration is essential
- Better agency coordination (e.g, with EPA) is essential.

Focus Question 3: Critical Focus Areas

Critical focus areas for the next 5 years

- Point-source CO_2 integration
  - Focus on improved CO_2 uptake efficiency, bioaccumulation

- Improve yields
  - Systems biology
  - Crop protection
- Extraction and HTL or other downstream processing
- Focus on cost reductions/CAPEX
- GMO: Scientific consensus on stability, environmental impact, etc., to present to regulatory community
  - e.g., guidance for EPA (green algae) and USDA/APHIS (cyanobacteria) and others
- Other ideas that were raised but given lower priority by the group
  - Process integration
  - Focus on energy-dense fuels
  - Money for crop protection
  - Acres on the ground buys down learning curve
  - Solid/liquid fuels from algae
  - Co-product value (long term, integrated)
  - Harvest: $/ton, efficiency, long term integrated
  - TEA now, LCA later.

Critical focus areas for the next 10 years

- Focus on resource utilization
  - Water and wastewater reuse integration in production
- Nutrient recycling
  - Bioaccumulation—strength or weakness
- LCA improvements.

"Ah-Ha" Moments from Morning Presentations

- Why are we still talking about fresh water modelling efforts? We should be building on these efforts and adding brackish and salt water resources to communicate the full potential of algae.
- Demonstrated proof of principle has been demonstrated at acre+ scales for many critical issues
- Industry hasn't done a good job of capturing sustainability advantages of algae production (e.g., fresh water use efficiency, etc.).

Focus Question 4: Barriers

- Policy and Regulation
  - Perceived uncertainty in Renewable Fuel Standard
  - Perceived lack of clarity in GMO approval pathways (EPA and USDA)
  - Lack of recognition from EPA for re-use pathways for CO_2 mitigation
- Systems thinking/analysis
  - Disconnect between R&D and highest impact areas to reduce system cost
  - Need increased access to off-the-shelf tools for TEA and LCA analyses and standard data formats

- Access to capital
  - Loan programs differ from agency to agency (and are generally expensive)
  - High-risk financing for first commercial facility is hard to secure (but critical to get across "valley of death")
- Access to high volume/low cost CO_2
- End user issues/collaboration & success stories
  - The 2013 Peer Review did not highlight many successes due to sensitive information that could not be revealed in a public environment; the industry needs to get better at communicating successes without revealing proprietary information.
  - More collaboration with engine testing groups needed.

Other ideas that were raised but given lower priority by the group

- Progress in primary harvest density (and R&D funding)
- Co-product opportunities and downstream conversion technologies (HTL vs. other approaches).

Focus Question 5: Next Steps

General: All of the showstopper-type barriers have been overcome in the last five years. The industry is now at a place where an economical algae biofuel production process can be attained through a concerted R&D effort, supported by DOE, to improve key process steps and increase revenue production, such as through commodity co-products.

- Policy and Regulation
  - Stable annual DOE budget for algae biofuels (DOE to double algae R&D request for FY 2016 to at least $30M; FE budget request for CO_2 utilization; increased budget consistent with cellulosic)
  - Engage NETL in future workshops
  - DOE budget request for algae funding in EERE's Advanced Manufacturing Office
  - Next few years is critical for many policy issues such as EPA pathway approval reform in place
- End-Users/Collaboration
  - Better communication of success stories
  - Invite engine and truck Coordinating Research Council (CRC) to ABO to encourage EPA/DOE funding with CRC champion
- Access to CO_2
  - Work with DOE's Office of Fossil Energy, DOE's National Energy Technology Laboratory, EPA
  - Metrics include $/ton delivered, recovery efficiency defined as percent CO_2 from source (stack) captured by algae
- Access to Capital
  - Coordinate meeting with USDA/DOE/all other key players to discuss financing opportunities
- Systems Thinking/Analysis
  - DOE should have technoeconomic map to drive down costs and drive R&D expenditures
  - Engage industry and include relevant pathways
  - $/ton/yr capital cost and $/ton operating cost for key steps
  - Focus R&D funding on reducing integrated system cost.

PROCEEDINGS: ANALYSIS AND SUSTAINABILITY

Focus Question 1: Breakthroughs and Accomplishments

- Harmonization work by Argonne National Laboratory, National Renewable Energy Laboratory (NREL), and Pacific Northwest National Laboratory integrated resource assessment (RA), LCA, and TEA for the entire system.
  - Sustainable siting, cultivation, harvest, dewatering and conversion to fuels were coupled with LCA and TEA analysis using a common set of assumptions, i.e., "harmonized."
  - TEA identifies cost drivers and how drivers from one step can influence another. An example is the trade-off between the cost to dewater algae versus the downstream conversion costs associated with more or less feedstock water.
  - The harmonization work illustrated a broader focus than just peak productivity and issues related to capacity use.
  - It was noted that Pan-Pacific Technologies (NAABB member) has also developed an Aspen-based algae model that is combined with Aspen Economic Analyzer. It couples biochemistry with thermodynamics.
- Development of infrastructure for data generation (from test beds, for example) is coming online and ability to generate replicable data
  - Increased industrial input and activity has also been beneficial.
  - Overall, this allows formulation of better production/conversion pathways using real data.
- GREET model with transparent assumptions
  - An example of a useful LCA tool; TEA models are less clear regarding underlying assumptions. Inconsistent assumptions make EROI and net energy ratio calculations difficult to compare.
- Validated growth model with published experimental data
- Spatially explicit resource analysis
  - Movement away from linear annual averages to more realistic nonlinear growth models that are spatially explicit
  - Avoiding use of annual averages and taking into account site-specific differences results in a much more meaningful analysis.

It was noted that analysis and sustainability considerations are included in funding opportunity announcement (FOA) language and are influencing the conversation about sustainability.

Focus Question 2: Lessons Learned

- There is a need for early and consistent data harmonization and a common language and set of metrics facilitated by synergistic collaborations (backward planning)
  - Collaborations lead to better and more complex analysis
  - Key sustainability indicators need to be addressed as design considerations
- Don't over-hype the potential of algal biofuels; we don't know it all yet.
  - This needs to be frequently asserted as there is still much to learn.
- It is important to establish good methods for extrapolation from lab to bench to field.
  - Good data are the foundation for all analysis. Basing an entire model solely on bench scale or theoretical data (worse) is to be avoided if that data doesn't well represent full-scale results, which can't be known fully until it is tested at large scale.
  - Scale-up validity and how to extrapolate: No standards are currently set regarding what the minimum scale should be from which data is extrapolated. This will be different for each aspect—growth models, harvest methods, dewatering methods, and conversion, for example.

- It is important to consider the variability of the complex natural systems involved in cultivating algae.
  - Critically important to consider the whole distribution system and not just peak or average production.
- Transparency in modeling and assumptions
  - It is difficult to compare the merits of different processes without clearly stated assumptions. This seems to be a problem with some TEAs. Publishing the models was suggested.
  - It is important to use real, curated data. Some of the growth data from NAABB, for example, has to be used carefully and needs to be properly reviewed before publication.
  - Modelers need to interact frequently with experimentalists and push for data justifying TEA assumptions, particularly regarding future targets. What do the experimentalists project as realistic targets, in what time frame, and how do they get there?

Focus Question 3: Critical Focus Areas

- Define sustainability and develop metrics to measure it.
  - Priority sustainability metrics may be different for different systems, and metrics defined for terrestrial feedstocks and conversion may not be applicable to algal systems. An example is the use of gallon fuel/ton biomass; gallon fuel/ton has more meaning for terrestrial biomass, whereas gallons/acre is more meaningful for algae.
  - All sustainability metrics should be considered positive, negative, or neutral.
  - Consider analyzing a 5-year life-cycle evaluation of CO_2 sources: Fossil vs. air capture.
  - Broader boundaries should be used for sustainability (not just plant boundaries); for example, regional water usage.
  - Include social impacts and social acceptability; this may be another example for which algal metrics are different from terrestrial metrics. How are algae farms viewed by the neighboring public?
  - Investigate non-obvious sustainability benefits beyond GHGs and footprints.
- Model risk and create dynamic models to capture cost impacts from risk.
  - Understand and harmonize the full range of risk: technical, environmental, economic, regulatory, supply chain, etc.
    - Different types of studies tend to focus on one or just a few different types of risk;
    - e.g., TEA focuses on technical and economic effects.
  - Understand whether pond crashes are preventable or whether we need to incorporate crash frequency in the analysis
  - Understand whether (and where) unlined ponds are acceptable from a sustainability perspective
- Integrate modeling to capture multiple dimensions of effects from algal production.
  - We critically need integrated LCA, TEA, economic impact, resource assessment modeling that are publically available and transparent documentation for data.
  - Nutrient recycle analysis needs to be incorporated, and methods need to be standardized.
- Develop a systematic performance model of the feedstock generation facility (farm); then integrate back to the downstream (conversion) experimental-based models.
  - Need a long-time horizon for research to better understand the effects operations have on each other
  - Develop site and regionally specific high-resolution models that are validated with experimental/field results
  - Standardize tools and language for models with industry, and make tools available to industry
  - Farm model specific to algae HTL needed with understanding and demonstration of potential improvements. Need to address data gap between farm model and conversion model
  - Define appropriate scale to be validated for models and targets
  - Baseline the $/gal results from NREL Aspen or other models; define the starting point for future comparisons.

- Modeling of waste streams and the impacts on multi-dimensional measures of sustainability
    - Characterize wastes; for example, are they waste streams or nutrient sources?

Focus Question 4: Barriers

Barriers revolve around data and how it is used.

- Challenge of providing access to industry data and results while maintaining confidentially; —balancing the need to retain IP rights with the need to inform sustainability metrics
    - Some existing data is inaccessible; for example, NAABB is taking a long time to be published; if the data still needs to be vetted or will not be published in a journal, how can it made available to others? How can it be requested?
    - Better cost modeling is needed, but will industry publish their production information?
- Lack of transparency in data and methods used to collect information
    - It is often difficult to interpret published data, for example, with regard to productivity: What was the time period and the growth conditions, etc.?
- Lack of standards for methods and analysis—drives inconsistent analysis
    - Lack in consistency—data needs to be standardized; for example, using a common method to calculate productivity
- Lack of systematic uncertainty analysis
    - Many pieces have to come together starting with growth and ending with fuel.
    - Need to have a method that takes into account the varying levels of technology readiness for each part.
- DOE has focused on two algae technology pathways; this has greatly facilitated modeling and analysis, but there is a question as to whether two pathways are sufficient.
    - DOE uses complete technology pathways that detail biofuel production systems from beginning to end (farm to fuel) as a means of showing periodic (usually annual) progress toward technical and economic goals. For example, terrestrial feedstocks R&D assumes an example feedstock, corn stover (for biochemical conversion) or wood (for thermochemical conversion), and models a conversion pathway that includes out-year improvements. This is not meant to imply that these are the only feedstocks or conversion pathways, but instead, they represent a baseline from which to measure improvements and compare to technology alternatives.
    - On the other hand, rigid pathways (such as those in BETO's Multi-Year Program Plan [MYPP]) can squeeze out innovations at a systems level; breakthroughs come from redesigning systems and not when specifications need to conform to specific parameters. This how the auto industry has made their advancements. There is a challenge with too many pathways; the issue is how to accommodate for different permutations without picking winners and losers.
    - Diversifying tools to add validity. Relying on a single model means we are dependent on model results, with no means of screening for errors. A second (potentially independent) model allows basis for comparison and ability to identify anomalies. Yet, having too many models has led to the effort to harmonize. Different models leads to different answers. Industry does not like duplication.
- Lower the barriers to entry to make it easier to use and produce modeling results.
    - Capture important feedback loops in models; for example, water and nutrient recycle.
    - Capture complexity.
    - What are the areas that are linear where we can focus modeling efforts? What makes the biggest impact in reliability of estimates?
    - Use the models to identify the cost drivers and key linkages.

Focus Question 5: Next Steps

- Continue to include integration constraints in FOA language as was done did in the 2013 Advancements in Algal Biomass Yield FOA.
  - Think of the overall system when data planning, not just individual operations. Integrating disciplines and/or unit operations should be a requirement in FOAs.
  - Systems integration should constrain the project plan: specify parameters, boundary conditions, and pathway details that modelers have to work within. How will one part affect another? For example, work on dewatering improvements needs to be coupled with the upstream source and the downstream use.
  - Other FOA requirement ideas
    - Planning for consistent data collection and its desired end use plus collaboration from outset should also be a part of FOA requirements
    - Sustainability should be in FOA language and sustainability metrics required in the project plan.
- Use analysis to determine helpful process constraints for experiments
  - Determine what the main drivers are for sustainability and use that information to shape models
  - More integrated, systematized products (data, models, language)
  - Improving access to transparent data (meaning the specifics of how the data were collected is reported)
- DOE-facilitated workshops and the development of shared language and experimental data
  - DOE should host technical workshops to get modelers together in combination with industry groups to talk about data collection methods, reporting, and use.
  - DOE fund a consortium similar to the Petroleum Environmental Research Forum.
  - Convey best practices from other communities (how do others outside of algal approach the problem?). Consider how NASA elicits desired data.
  - How can ABO play a part?
  - Community should provide input on what DOE should report out on. Crowd sourcing as a way to problem solve—open problems up to public to see if they can solve them.
- Build better lab-modeling-scale connections in experimental design and data collection
  - What is the minimum scale for data collection that is meaningful? This will be different for each part of the system.
- Models need to be used to address high-impact sustainability drivers
  - Create a consistent pathway for algae
  - Labs and industry are on different scales—how can the data be reconciled?
  - Incorporate complexity and uncertainty analysis (not just one variable at a time sensitivity)
  - Document model validation—data pedigree, how analysis is done and checked against real data.
  - Communicate critical information that model conveys—make sure everybody is on same page about needs and what model produces. To do this, the models must be transparent, publically available, and have integrated parts.
- Facilitate data management and standardization and dissemination
  - RAFT was a good model that worked well. Stick with that model.
  - NAABB had some good ideas regarding data collection and hydrodynamic modeling.
  - Make data management the subject of an algae-specific workshop.
  - Have infrastructure to enable input of data, and lower the barrier to entering and using data; for example, the Bioenergy Knowledge Discovery Framework (KDF) is a way to disseminate information; another example is the Idaho National Laboratory R&D library. These are open access and curated databases.

    - Collect and use lessons learned from experience modelers for use by new modelers
    - Public database of costs and assumptions.
- Develop technical standards
    - Harmonization is a good example of where to start; transparent, available, integrated LCA, TEA, RA
    - DOE should sponsor a technical standards committee
    - Engagement of the community—particularly with industry (this is a major barrier for labs). Is it possible to work with industry? Industry values systems analysis, but it's not guiding systems research being conducted in labs.
    - Creating, maintaining, and distributing harmonization results.
    - Need for a standard language: Make sure the algae field understands what terms mean; standard language has improved a lot already, but it hasn't translated into standard data collection.

CLOSING REMARKS

As evident in this workshop proceedings report, DOE received significant feedback from Algal Biofuels Strategy Workshop participants. Algae Program personnel participated in the workshop discussions and have reviewed the information provided in this report. DOE will consolidate feedback received from both the fall 2013 and spring 2014 workshops and report back to the algae community at *Biomass 2014*, BETO's annual conference in Washington, D.C.

BETO would like to express our thanks to all of the participants for their time, efforts, and contributions. The discussions and information provided through the Open Forum and the Breakout Sessions are extremely valuable to the Algae Program, and we look forward to continued collaboration as we utilize this feedback to inform program strategies moving forward.

APPENDIX A: WORKSHOP AGENDA

ALGAL BIOFUELS STRATEGY—SPRING WORKSHOP Charleston Marriott | 170 Lockwood Blvd, Charleston, South Carolina 29403			
Start Time	*End Time*	*Item*	*Speaker*
		Wednesday March 26, 2014—Day 1	
7:30 a.m.	5:00 p.m.	**Registration**	
7:30 a.m.	8:30 a.m.	**Continental Breakfast—Provided**	
8:30 a.m.	9:10 a.m.	**Algae R&D Portfolio Overview** Opening Remarks Consortia Outcomes and Peer Review Program Challenges and Strategy (MYPP and Technical Targets) Workshop Agenda and Objectives ATP3 Testbeds Overview	Daniel Fishman, *Algae Technology Manager*
9:10 a.m.	9:30 a.m.	**Q&A Period**	All
9:30 a.m.	9:50 a.m.	**Break**	
9:50 a.m.	10:30 a.m.	**BETO Technology Pathways Panel** Review of the Algal Lipid Upgrading and Hydrothermal Liquefaction pathways Update on Harmonization Effort Q&A Session	Pacific Northwest National Laboratory National Renewable Energy Laboratory Argonne National Laboratory
10:30 a.m.	12:30 p.m.	**Open Forum Discovery Presentations** Five-minute briefings from participants on topics of their interest, suggested focus on achievements to-date, current barriers, and outlook	Participants selected in advance of Workshop.
12:30 p.m.	1:30 p.m.	**Lunch—Provided**	
1:30 p.m.	3:30 p.m.	**Breakout Session One** Five concurrent technical sessions focused on understanding the implications of achievements to-date and emergent challenges to continued advancement. Topic Tracks: (1) Algal Biology, (2) Cultivation, (3) Processing and Conversion, (4) Scaling and Integration, and (5) Analysis and Sustainability.	Facilitated Discussions
3:30 p.m.	3:50 p.m.	**Break**	
3:50 p.m.	4:00 p.m.	**Workshop Overview** Brief review of fall workshop; results and how it informed the topic areas for the spring workshop	Christy Sterner, *Algae Technology Manager*
4:00 p.m.	5:00 p.m.	**Report-Out from Breakout Session One**	

ALGAL BIOFUELS STRATEGY—SPRING WORKSHOP Charleston Marriott | 170 Lockwood Blvd, Charleston, South Carolina 29403			
Start Time	*End Time*	*Item*	*Speaker*
Thursday March 27, 2014—Day 2			
7:30 a.m.	8:00 a.m.	**Continental Breakfast—Provided**	
8:00 a.m.	8:05 a.m.	**Convening of Day 2** Brief listing of each breakout session topic for the day	Daniel Fishman, *Algae Technology Manager*
8:05 a.m.	10:05 a.m.	**Breakout Session Two** Continued technical sessions discussions focused on strategies for advancing algal biofuels. Sessions remain broken by five topical areas and moderated by selected chairs.	Facilitated Discussions
10:05 a.m.	10:20 a.m.	**Break**	
10:20 a.m.	11:20 a.m.	**Report-Out from Breakout Session Two**	Topic Chairs
11:20 a.m.	11:30 a.m.	**Meeting Adjournment** Action Items Next Steps Closing Comments	Daniel Fishman, *Algae Technology Manager*

APPENDIX B: OPEN FORUM DISCOVERY PRESENTATIONS

Speaker	Affiliation	Presentation Title
Ken Birnbaum	New York University	Experimental Evolution on Lipid Content Using Fluorescence-Based Selection
Wayne Yuan	North Carolina State University	Biological Lysis of Microalgal cells
Jennifer Stewart	University of Delaware	Algal Biology—Autoflocculation
Deborah Newby	Idaho National Lab	Polyculture is a Reality of Algal Biofuel Production
Wayne Curtis	Penn State University	Hydrocarbon Metabolic Engineering (from Algae)
Ken Reardon	Colorado State University	Light Exposure Issues in Cultivation Systems and Effects on Algal Physiology
Mark Huntley	Cornell Consortia	Marine Algal Biofuels Consortium
Kef Kasdin	Proterro	Making Sugar from CO_2
Michael Wilson	University of Kentucky	From Coal Flue Gas to Fungible Fuels
John Marano	JM Energy Consulting	Deploying Algaculture for CO_2 Capture
Tryg Lundquist	California State Polytechnic University	Research Needs for Nutrient and Water Recycling in Algae Biofuels Cultivation
Dean Calahan	Smithsonian Institute	A New Dimension in Algae Farming
David Blersch	Auburn University	Review of Biomass Productivity and Quality from Pilot-Scale Algal Turf Scrubbing Installations
Armin Volkel	Parc	Innovative Technology for Algae Dewatering
John Pellegrino	University of Colorado	Development of an Extractive Membrane Photobioreactor to Harvest Secreted Fuel Precursors and Metabolites from Algae
Babetta Marrone	Los Alamos National Lab	Ultrasonic Technology for Algae Harvesting, Extraction, and Separation
Umakanta Jena	Desert Research Institute	Hydrothermal Processing of Algae in Hot, Compressed Water
David Hazlebeck	Global Algae Innovations	Recent Progress Puts Algae Biofuels Within Reach
Craig Behnke	Sapphire Energy	Sapphire Energy Integrated Biorefinery
Martin Sabarsky	Cellana	Second-Generation Biofuels from Multi-Product Biorefineries Combine Economic Sustainability with Environmental Sustainability
Pat Ahlm	Algenol	Algenol Technology Status Update
Jason Quinn	Utah State University	Future Modeling Needs: Growth, TEA, and LCA
Lawrence Sullivan	Trident Technical College	Quick Review of Capital Asset Pricing Model and ROCE Modeling of Investments
Rebecca Efroymson	Oakridge National Lab	Sustainable Development of Algae for Biofuel
Kim Ogden	University of Arizona	RAFT Partnership
Sarah Studer	Department of Energy	Algal Research Challenges
Margaret McCormick	Algae Biomass Organization	State of the Industry and Survey

APPENDIX C: ABBREVIATIONS AND ACRONYMS

ABO	Algae Biomass Organization
ALU	Algal lipid upgrading
ANL	Argonne National Laboratory
AD	Anaerobic digestion
ASTM	American Society for Testing and Materials
ATP3	Algae Testbed Public-Private Partnership
BAT	Biomass assessment tool
BETO	Bioenergy Technologies Office
CAAFI	Commercial Aviation Alternative Fuels Initiative
CAPEX	Capital expenditure
CO_2	Carbon dioxide
CRC	Coordinating Research Council
DOD	Department of Defense
DOE	Department of Energy
EA	Environmental Assessment
EERE	Office of Energy Efficiency and Renewable Energy
EPA	Environmental Protection Agency
EROI	Energy return on investment
FE	Office of Fossil Energy
FOA	Funding opportunity announcement
gge	Gallon gasoline equivalent
GHG	Greenhouse gas
GM	Genetically modified
GMO	Genetically modified organism
HTL	Hydrothermal liquefaction
IP	Intellectual property
IPM	Integrated Pest Management
LANL	Los Alamos National Laboratory
LCA	Life cycle analysis
N	Nitrogen
NAABB	National Alliance of Advanced Biofuels and Bioproducts
NABC	National Advanced Biofuels Consortia
NEPA	National Environmental Protection Act
NETL	National Energy Technology Laboratory
NGO	Non-governmental organization
NIST	National Institute of Standards and Technology
NREL	National Renewable Energy Laboratory
OPEX	Operating expenditure
ORNL	Oakridge National Laboratory
OS	Office of Science
P	Phosphorous
PBR	Photobioreactor
PNNL	Pacific Northwest National Laboratory
RA	Resource assessment
R&D	Research and development
RAFT	Regional Algae Feedstock Testbed
RFI	Request for Information
RFS	Renewable Fuel Standard
SBIR	Small Business Innovation Research
TAN	Total acid number
TEA	Technoeconomic analysis
TRL	Technology Readiness Level
TSCA	Toxic Substances Control Act
USDA	United States Department of Agriculture
WW	Wastewater

APPENDIX D: ATTENDEES

The following is a list of those Algal Biofuels Strategy Workshop participants who elected to share their contact information in these proceedings.

Sushil Adhikari
Associate Professor
Auburn University
215 Tom Corley Building
Auburn, AL 36849
sza0016@auburn.edu

Patrick Ahlm
Assistant Director,
Government & Regulatory Affairs
Algenol Biofuels Inc.
16121 Lee Road, Suite 110
Ft. Myers, FL 33912
239-444-6313
pat.ahlm@algenol.com

Toby Ahrens
Senior Scientist
BioProcess Algae
88 Silva Lane, Tech 4
Suite 250
Middletown, RI 2842
207-233-7893
tobyahrens@bioprocessalgae.com

John Aikens
CTO
Proterro
125 Windsor
Suite 126
Oak Brook, IL 60526
630-575-8313
jaikens@lybradyn.com

Mark Allen
Vice President - Integrated Carbon Solutions
Accelergy Corporation
22 Mule Deer Trail
Littleton, CO 80127
mallen@accelergy.com

Joe Anderson
President
Recycle Carbon Dioxide, Corporation
4805 Highland Ave
Downers Grove, IL 60515
630-963-5999
joeanderson993@gmail.com

Matthew Atwood
President & CEO
Algae Systems LLC
6321 Jordan Road
Daphne, AL 36526
847-800-6696
matwood@algaesystems.com

Christopher Bagwell
Fellow Scientist
Savannah River National Laboratory
227 Gateway Drive
Bldg 999-W
Aiken, SC 29808
803-819-8465
christopher.bagwell@srnl.doe.gov

Craig Behnke
Sr. Director, Cultivation
Sapphire Energy, Inc.
3115 Merryfield Row
San Diego, CA 92121
858-210-2308
craig.behnke@sapphireenergy.com

Alexander S. Beliaev
Scientist
Pacific Northwest
National Laboratory
902 Battelle Boulevard
PO Box 999, MSIN K9-33
Richland, WA 99352
509-371-6966
alex.beliaev@pnnl.gov

Halil Berberoglu
Assistant Professor
The University of Texas at Austin
204 E. Dean Keeton Street
Stop C2200
Austin, TX 78712
310-254-4768
halil.berberoglu@gmail.com

Kenneth Birnbaum
Associate Professor
New York University
New York University
12 Waverly Place
NY, NY 11218
718-702-0266
ken.birnbaum@nyu.edu

David Blersch
Assistant Professor
Auburn University
Biosystems Engineering Department
200 Corley Building
Auburn, AL 36849
334-844-3542
dmb0040@auburn.edu

Larry J. Boyleston
Senior Project Manager
SCRA
330 Yachting Road
Lexington, SC 29072
803-960-7811
larry.boyleston@scra.org

Andrew Braff
Attorney
Wilson Sonsini Goodrich & Rosati
701 Fifth Avenue
Suite 5100
Seattle, WA 98104
abraff@wsgr.com

Dean Calahan
Ph.D.
Smithsonian Institution
Department of Botany, MRC-164,
Smithsonian Inst.
PO Box 37012
Washington, DC
calahans@si.edu

Ryan Collins
University of South Carolina
1006 Marion St
Apt. D
Columbia, SC 29201
803-341-0909
collinr3@email.sc.edu

Rhykka Connelly
Program Manager
University of Texas Bioproducts and Bioenergy Program
JJ Pickle Research Campus
10100 Burnet Rd., EME133
Austin, TX 78758
409-392-3624
r.connelly@cem.utexas.edu

Wayne Curtis
Professor of Chemical Engineering
The Pennsylvania State University
226B Fenske Laboratory
University Park, PA
814-863-4805
wrc2@psu.edu

Ryan Davis
Sandia National Laboratories
7011 East Ave
Dept 8634, MS9671
Livermore, CA 94550
925-294-4805
rwdavis@sandia.gov

Thomas Dempster
Associate Research Professor
Arizona State University
4718 E. Innovation Way South
Mesa, AZ 85212
480-320-0213
dempster@asu.edu

Meghan Downes
Associate Professor
New Mexico State University
MSC 3CQ
PO Box 30001
Las Cruces, NM 88003
575-202-5181
cdownes@nmsu.edu

Alexander Drake
Energy and Cleantech Government Affairs Advisor
Wilson Sonsini Goodrich & Rosati
1700 K St NW
Fl 5
Washington, DC 20006
202-973-8852
adrake@wsgr.com

Andrew Dunn
Director of Residential and Commercial Solar Sales & Marketing
Sustainable Energy Solutions
653A Windermere Blvd.
Charleston, SC 29407
706-202-5404
sciadunn@uga.edu

Rebecca Efroymson
Senior Scientist
Oak Ridge National Laboratory
PO Box 2008
Oak Ridge, TN
828-505-1673
efroymsonra@ornl.gov

Ed Frank
Argonne National Laboratory
9700 S Cass Ave
Argonne, IL 60439
efrank@anl.gov
Wilson Gautreaux
Manager, Environmental Projects
Rayonier Performance Fibers
1106 South Palm Street
Jesup, GA
843-364-0603
wilsongautreaux@gmail.com

Daniel Geller
The University of Georgia
Driftmier Engineering Center Annex 597
D W Brooks
Annex room 104
Athens, GA 30602
706-583-0000
dgeller@uga.edu

Valerie Harmon
Sr. Director of Research & Development
Cellana LLC
73-4460 Queen Kaahumany Hwy
Box 127
Kailua Kona, HI 96740
808-334-1690
tina.lepage@cellana.com

Charles Harper
President / Founder
Simbuka Energy, LLC / Ready-4-School Rwanda
414 S Ithan Ave
Villanova, PA 19085
CLHarperJr@gmail.com

David Hazlebeck
Chief Executive Officer
Global Algae Innovations Inc.
PO Box 19623
San Diego, CA 92020
619-884-3206
davidhazlebeck@globalgae.com

Michael Heitkamp
Biotechnology Research Manager
Savannah River National Laboratory
Bldg 999-W
Savannah River Site
Aiken, SC 29803
803-819-8404
michael.heitkamp@srnl.doe.gov

Richard Hess
Division Director, Energy Systems & Technologies
Idaho National Laboratory
PO Box 1625
Idaho Falls, ID
208-526-0115
jrichard.hess@inl.gov

Ryan Hunt
Chief Technology Officer
ALGIX, LLC
198 Ben Burton Circle
Bogart, GA 30622
706-224-1224
rwhhunt@gmail.com

Umakanta Jena
Assistant Professor
Desert Research Institute
2215 Raggio Pkwy
Reno, NV 89512
775-674-7122
umakanta.jena@dri.edu

Susanne Jones
Senior Research Engineer
Pacific Northwest National Laboratory
PO Box 999
MSIN P8-60
Richland, WA 99352
sue.jones@pnnl.gov

Moshan Kahandawala
Group Lead, Bioenergy and Carbon Mitigation Group
University of Dayton Research Institute
SPC Room 1191
300 College Park Avenue
Dayton, OH 45419
Moshan.Kahandawala@udri.udayton.edu

John Kamins
Vice President
Evotec Inc.
6 Twin Eagles Ct
Hawthorn Woods, IL 60047
773-558-9523
john.kamins@evotec.com

Kef Kasdin
CEO
Proterro, Inc.
100 Princeton South Corp Center
Suite 150
Ewing, NJ 8628
kef@proterro.com

Christopher Kinchin
Biorefinery Analysis Engineer
National Renewable Energy Laboratory
1617 Cole Blvd
RFS-201
Denver, CO
303-384-7709
christopher.kinchin@nrel.gov

Victoria Kurtz
Sales Manager - Algae Technology
Fluid Imaging Technologies, Inc.
200 Enterprise Drive
Scarborough, ME 4074
207-289-3231
victoria@fluidimaging.com

Jeffrey Lacey
Idaho National Laboratory
PO Box 1625
MS 2203
Idaho Falls, ID 83406
208-526-7010
jeffrey.lacey@inl.gov

Todd Lane
Principal Member of Technical Staff
Sandia National Laboratories
PO Box 969
MS 9292
Livermore, CA
925-294-2057
twlane@sandia.gov

Ken Langley
Senior Market Development Manager
Waters Corporation
34 Maple Street
Milford, MA 1757
508-341-4523
ken_j_langley@waters.com

Lieve Laurens
Scientist
National Renewable Eneregy Laboratory
15013 Denver West Parkway
Golden, CO 80401
303-384-6196
Lieve.Laurens@nrel.gov

Ira Levine
University of Southern Maine
51 Westminster Street
Lewiston, ME 4240
207-753-6588
ilevine@usm.maine.edu

Rachel Levinson
Director, national research initiatives
Arizona State University
1834 Connecticut Ave., NW
Washington, DC 20009
Rachel.levinson@asu.edu

Ji Li
University of Maryland
1422 Animal Science Building
University of Maryland
College Park, MD 20742
jili@umd.edu

Cynthia Ludwig
DIrector, Industry Relations
AOCS
PO Box 17190
Urbana, IL 61803
217-359-2344
cynthia.ludwig@aocs.org

John Marano
Presiident
JM Energy Consulting, Inc.
1065 South Lake Dr.
Gibsonia, PA 15044
724-625-5466
jmarano@jmenergyconsulting.com

Sergei Markov
Professor
Austin Peay State University
Biology Department, P.O. Box 4718
Clarksville, TN 37044
931-221-7440
markovs@apsu.edu

Babetta Marrone
Ph.D. Scientist/Biofuels Program Manager
Los Alamos National Laboratory
M888
Los Alamos, NM 87545
505-667-3279
blm@lanl.gov

Jason Masters
Energy Manager
US Army Corps of Engineers
229 North Donar Dr.
Columbia, SC 29229
jason.c.masters.civ@mail.mil

Teresa Mathews
Research Scientist
Oak Ridge National Laboratory
1 Bethel Valley Rd
Oak Ridge, TN 37831
865-241-9405
mathewstj@ornl.gov

Peter May
Senior Environmental Scientist
Biohabitats/University of Maryland
2081 Clipper Park Rd
Baltimore, MD 21211
pimay@umd.edu

Michael McCartney
President
Ecos Environmental Health Foundation
4980B Prince Edward Road One
Consecon, ON
613-399-5857
mccartneymj@mac.com

Margaret McCormick
CEO
Matrix Genetics
1600 Fairview Ave E
Suite 300
Seattle, WA 98102
206-355-5289
mmccormick@matrixgenetics.com

John McGowen
Director of Operations and Program Management
Arizona Center for Algae Technology and Inovation, Arizona State University
7418 E. Innovation Way South
ISTB3-103
Mesa, AZ 85212
480-727-1472
john.mcgowen@asu.edu

Hiro Mochizuki
Research Coordinator
University of Tsukuba
1-1-1 Tennoudai
Tsukuba City, JAL
+81 (29) 853-6869
mochizuki.hiroyuk.fu@un.tsukuba.ac.jp

Evan Munning
Mechanical Engineer Sales Engineer
Everything Automotive
73 Pollard Rd
Mountain Lakes, NJ 7046
732-763-6315
enm3@njit.edu

Michael Munning
Owner/Designer/Innovator
Everything Automotive - Bio-Diesel Solutions
426 19th Ave
Brick, NJ 8724
973-997-8457
michael.munning@gmail.com

Nick Nagle
Bioprocess Engineer
National Renewabel Energy Laboratory
16173 Denver West Parkway
Golden, CO 80401
303-384-6184
nick.nagle@nrel.gov

Robert Natelson
North Carolina State University
2701 Homestead Road
Apartment # 1004
Chapel Hill, NC 27516
215-913-9582
rhnatels@ncsu.edu

Deborah Newby
Senior Staff Scientist
INL
2525 Fremont Ave
Idaho Falls, ID 83415
208-526-7779
deborah.newby@inl.gov

Jim Neylon
New Business Development
ITECS
608 Faulkner St
New Smyrna Beach, FL 32168
772-538-9530
jneylon@itecs-innovative.com

Lucie Novoveska
Algae Systems
6321 Jordan Rd
Daphne, AL 36526
lnovoveska@algaesystems.com

Kimberly Ogden
Professor
University of Arizona
1133 E. James E Rogers Way
Tucson, AZ 85721
520-621-9484
ogden@email.arizona.edu

Min Park
Senior Staff Scientist
LANL
M888, Bioscience Division
Los Alamos National Laboratory
Los Alamos, NM 87545
minsungpark0@kaist.ac.kr

John Pellegrino
Professor Research
University of Colorado
Dep't of Mechanical Engineering
MS427
Boulder, CO 80302
303-735-2831
john.pellegrino@colorado.edu

Phil Pienkos
Principal Group Manager
NREL
15013 Denver West Parkway
Golden, CO 80401
303-384-7973
Philip.Pienkos@nrel.gov

Yan Poon
Director
Sapphire Energy, Inc.
3115 Merryfield Row
San Diego, CA 92121
858-768-4751
yan.poon@sapphireenergy.com

Laurie Purpuro
Government Affairs Advisor
K&L Gates
1601 K St., NW
Washington, DC
703-989-0978
laurie.purpuro@klgates.com

Jason Quinn
Utah State University
4130 Old Main Hill
Logan, UT 84322
970-581-7992
jason.quinn@usu.edu

David Raney
President
Raney Associates
812 Camino Viejo
Santa Barbara, CA 93108
805-969-6108
david@draneyassociates.com

Ken Reardon
Professor
Colorado State University
1370 Campus Delivery
Fort Collins, CO
970-491-6505
kenneth.reardon@colostate.edu

Tassos Recachinas
President
HDS International Corp.
10 Dorrance St.
#700
Providence, RI 2903
401-400-0028
tdr@hdsicorp.com

Martin Sabarsky
CEO
Cellana LLC
73-4460 Queen Kaahuman Hwy
Suite 127
Kailua-Kona, HI 96740
858-774-7915
martin.sabarsky@cellana.com

Richard Sayre
Senior Research Scientist
Los Alamos National Laboratory
100 Entrada Dr
Los Alamos, NM 87544
505-412-6532
rsayre@newmexicoconsortium.org

Susan Schoenung
Longitude 122 West, Inc.
885 Oak Grove Avenue
Suite 304
Menlo Park, CA 94025
650-329-0845
longitude122west@gmail.com

Rajdeep Shakya
Auburn University
200 Corley Building
Auburn, AL 36849
rzs0035@tigermail.auburn.edu

Curtis Snow
Seattle Lunar Group
21698 98th Ave South
Kent, WA 98031
curtis@dbug.org

Susan Stagg-Williams
Professor
University of Kansas
1530 w 15th Street
Room 4142 Learned Hall
Lawrence, KS 66045
785-864-2919
smwilliams@ku.edu

Ellen Stechel
Arizona State University - LightWorks
PO Box 875402
Tempe, AZ
Ellen.Stechel@asu.edu

Jennifer Stewart
Scientist
University of Delaware
700 Pilottown Road
Lewes, DE 19958
302-645-4371
Jen@udel.edu

Kimble Strickland
TBD
5400 Walking Stick lane
North Charleston, SC 29420
843-814-4192
kimble61@att.net

Ben Stuart
Executive Director, Institute for Sustainable Energy and the Environment
Ohio University
122 Stocker Center
Athens, OH 45701
740-591-7719
stuart@ohio.edu

Sarah Studer
EERE Postdoctoral Fellow, Fuel Cell Technologies Office
ORISE
1000 Independence Ave. SW
Washington, DC 20585
sarah.studer@ee.doe.gov

Lawrence Sullivan
Faculty
Trident Technical College
7000 Rivers Avenue
Charleston, SC 29406
651-269-7737
lawrence.sullivan@tridenttech.edu

Rebo Sullivan
5337 Thayer Drive
Raleigh, NC 27612
919-523-2723
ncbiodiesel@yahoo.com

Emily Trentacoste
NOAA
1315 East-West Highway, Suite 12603
Silver Spring, MD 20910
703-501-8682
emily.trentacoste@noaa.gov

Peter Valdez
Algae Systems
6321 Jordan Rd
Daphne, AL 36526
575-517-0685
pvaldez@algaesystems.com

Sasidhar Varanasi
Professor of Chemical Engineering
The University of Toledo
Chemical Eng.; MS 305; Room # 3062
Nitschke Hall
2801 West Bancroft Street
Toledo, OH 43606
419-530-8093
sasidhar.varanasi@utoledo.edu

Albert Vitale
VP
Commercial Algae Management
102 Heron Lake Rd
Franklin, NC 28734
561-713-8619
acvitale@gmail.com

Robert Vitale
President
Waterwheel Factory
320 Arbor Lane
Franklin, NC 28734
828-369-5928
waterwheel@dnet.net

Armin Volkel
Palo Alto Research Center
3333 Coyote Hill Rd
Palo Alto, CA 94304
avolkel@parc.com

William Waggoner
Air and Energy Research
426 S. Green Valley Lane
St. George, UT 84770
kwaggoner@airandenergyresearch.com

Terry Walker
Professor
Clemson University
114 BRC
Clemson, SC 29634
walker4@clemson.edu

Mark Wigmosta
Chief Scientist
Pacific Northwest National Laboratory
902 Battelle Boulevard
PO Box 999, MSIN K9-33
Richland, WA 99352
509-372-6238
mark.wigmosta@pnl.gov

Michael Wilson
Research Engineer
University of Kentucky Center for
Applied Energy Research
2540 Research Park Drive
Lexington, KY 405011
michael.wilson@uky.edu

Carla Wood, Ph.D.
Consultant
Lawrence D. Sullivan & Company, Inc.
111 Olympic Club Drive
Summerville, SC 29483
651-214-2995
cmwood369@hotmail.com

May Wu
Principal Environmental System Analyst
Argonne National Laboratory
9700 S. Cass Avenue
Lemont, IL 60439
mwu@anl.gov

Wenqiao Yuan
North Carolina State University
265 Weaver Labs
North Carolina State University
Raleigh, NC 27695
wyuan2@ncsu.edu

Tim Zenk
Vice President of Corporate Affairs
Sapphire Energy, Inc.
3115 Merryfield Row
San Diego, CA 92130
858-768-4755
tim.zenk@sapphireenergy.com

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