Bioenergy Technologies Office – FY19 Multi-Year Plan

Technical Barriers and Challenges

BETO Level Barriers and Challenges

Ot-A. Availability of Quality Feedstock: There are a variety of technical, operational, and economic uncertainties in the availability of consistent and affordable quality feedstock supplies. Mobilizing large volumes of untapped resources will require establishing advanced supply chains to improve quality and will require significant changes to agricultural and forestry practices. Costs associated with grower inputs, establishing new supply chain infrastructure, and preprocessing to improve feedstock quality constrain the overall cost reduction potential for biomass. To meet quality requirements of conversion facilities, feedstock supply and logistics R&D will need to improve feedstock quality from harvest and collection through delivery while also meeting conversion performance and cost goals.

Ot-B. Cost of Production: Significant R&D is required to develop highly efficient and robust feedstock handling, pre-processing, and conversion processes to compete with conventional petroleum fuels. The distributed nature of biomass and waste streams requires greater conversion efficiency at smaller scales compared to petroleum refineries. This drives research in process integration, systems efficiencies, and advanced, robust separations and molecular efficiency to convert current waste streams (an expense) into desirable products (a revenue). This includes developing innovative ways to derive higher values from all primary and secondary product streams (such as lignin and carbon dioxide). As with petroleum refineries, product slates will need to include bioproducts to spread the costs of production across biofuels and higher-valued bioproducts to be competitive in commodity markets.

Ot-C. Risk of Financing Large-Scale Biorefineries: Obtaining traditional financing is a challenge for new innovative bioenergy technologies, and most pioneer commercial-scale facilities require equity financing of $200 million or more. Biorefineries face significant first-of-a-kind risks in technology. For investors to gain confidence in a technology, processes must function efficiently and reliably with the full variability of feedstocks for significant lengths of time to reduce uncertainty around process capability and verify that different newly developed technologies can be integrated successfully into a complete, reliable system. Investors also need assurance that operational performance can be scaled

Pm-A. Strategy and Goals: To reach overall national goals for bioenergy, Office and Program-level strategies and goals need to be developed that are based on national goals, administrative and legislative priorities, and DOE and EERE strategic goals and priorities. BETO vision and mission and BETO strategic and performance goals need to be updated to maintain alignment with changing priorities and the needs of a a developing technology landscape.

Pm-B. Program Plans and activities: Based on overall office and Program goals, programs need to develop plans aligned with overall goals and priorities that identify technical challenges and barriers based on stakeholder input and technology evaluation. Program budgets need to be prioritized and aligned with Office level goals and plans as they are updated in the Multi-Year Plan and based on technology progress tracked in the Multi-Year Plan Technical Addendum.

Pm-C. Project solicitations and project plans: Based on program goals and plans, programs need to determine performers through competitive solicitations or direct laboratory funding. Selected project proposals need to lay out an explicit plan that aligns with BETO office and program priorities expressed in the MYP and MYPTA.

Pm-D. Performance assessment: BETO needs to assess progress, decisions, goals, and approaches by monitoring and evaluating program and project performance. The performance assessment activities provide avenues for input from other government agencies, stakeholders, and independent expert reviewers on program effectiveness and progress toward BETO's mission and goals.

Feedstock Supply & Logistics R&D Barriers and Challenges

Ft-A. Feedstock Availability and Cost: Conversion technologies face a variety of technical, operational, and economic uncertainties in the availability of consistent and affordable feedstock supplies, and in the unreliability of supply and logistics systems due to lack of fundamental understanding of biomass properties and biomass's unique material handling challenges. Complete data on volumes, biomass properties, and characteristics by geographic location are needed to design and develop economical feedstock-conversion processes.

Ft-B. Production: The production systems and performance of energy crop species are not well-characterized. The range of production-scale yields of energy crops across genetics, environments, and agronomic practices is not fundamentally understood and requires comprehensive characterization and reliable data from real-world production operations. Scientific information is still lacking on new varieties/cultivars of energy crops, to inform the degree to which they show performance improvements relative to better characterized predecessor varieties, how well adapted they are across regions, whether they may be more cost-effective to produce, and whether they can be shown to be more sustainable relative to a control variety and/or traditional cropping/pasture systems.

Ft-C. Feedstock Genetics and Variety Improvement: The productivity and robustness of bioenergy crops is not optimized for bioenergy applications, and could be significantly increased by traditional breeding and selection and/or modern genetic engineering technologies. Reduced production uncertainty associated with more stress-tolerant varieties is needed to encourage farmers, biorefineries, and financial institutions to seriously consider energy crops in the mix of crops they produce and process.

Ft-D. Sustainable Harvesting: Current crop harvesting machinery is unable to selectively harvest preferred components of cellulosic biomass (e.g., stems versus leaves) to meet the capacity, efficiency, quality, or delivered requirements of biorefineries, while maintaining acceptable levels of soil carbon and minimizing soil contamination, compaction, and erosion. Harvest, collection, and transport systems and equipment are not optimized for bioenergy production. Logistics costs need to be reduced while improving biomass quality and processing efficiency.

Ft-E. Feedstock Quality: Monitoring and Impact on Preprocessing and Conversion Performance: The physical, chemical, microbiological, and post-harvest physiological variations in biomass arise from differences in genetics, relative crop maturity, agronomic practices and harvest methods employed, soil type, geographical location, and climatic patterns and events; their impacts on logistics, conversion, and processes economics are not fundamentally understood. Available data and information are extremely limited to identify the key physical (e.g., particle size, shape, pore volume, surface area, bulk density, and thermal conductivity), mechanical (e.g., compressibility, yield stress, shear, cohesion, friction, and rheological behavior), and chemical (e.g., moisture, ash content/speciation, carbohydrate, lignin content/speciation, extractives, and problematic contaminants) quality characteristics of feedstocks, and to understand the magnitude of their impacts on feeding, preprocessing, and conversion performance (e.g., throughput, yield, and equipment failure). Methods and instrumentation are also lacking for quickly, accurately, and economically measuring these quality-related properties. Analytical and processing standards, understanding of causal relationships and mechanisms at molecular level, and quality specifications for cellulosic feedstocks are not well developed and may vary from one conversion process to another.

Ft-F. Biomass Storage Systems: Current biomass storage systems (especially for wet, herbaceous materials) often result in dry matter loss and degraded biomass quality between the time of harvest and use. Inconsistent moisture content in the stored biomass lead to storage-related physical and chemical degradation, poor feeding and handling performance, and periodic shutdown related to mill and conveyor plugging. The effect of different storage methods and moisture management is not adequately defined to enable design of cost-effective systems that minimize dry matter loss, preserve the biomass quality, and increase the stability of downstream operations.

Ft-G. Biomass Physical State Alteration: The initial sizing and grinding, cell wall structure, and particle characteristics of cellulosic biomass affect conversion efficiencies and yields of all downstream conversion operations. To design technologies and equipment to economically process biomass-derived feedstocks to conversion specifications, information is needed on how the specific differences in the physical and mechanical properties of each feedstock at the nano- and micro-scale impact feed handling as well as conversion cost and yields.

Ft-H. Biomass Material Handling and Transportation: Raw herbaceous biomass has very low bulk and energy density, making it costly to transport, and conventional handling systems cannot cost-effectively deliver high volumes of herbaceous biomass. Current handling and transportation systems designed for higher moisture woodchips are not optimized for bioenergy processes.

Ft-I. Feedstock Supply System Integration and Infrastructure: Conventional supply systems used to harvest, collect, store, preprocess, handle, and transport biomass are not designed to satisfy the large-scale needs of a nationwide system of integrated biorefineries. The infrastructure for feedstock logistics has not been defined for the potential variety of locations, climates, feedstocks, storage methods, and processing alternatives that will need to be implemented on a national scale.

Ft-J. Operational Reliability: Recent evidence indicates that IBR development and operation have suffered from failing to account for the complexity and variability of lignocellulosic biomass, inconsistent feeding and handling, poor equipment design, and flawed integration. To reach cost-effective operation, biorefineries need to operate at a design capacity of at least 90% on-stream reliability. Improvements to operational reliability are modeled as a compounded percentage of feedstock and biofuel design capacity based on progress against key limiting factors. Fundamental R&D is needed to identify the key feedstock quality and operation factors affecting operational reliability, develop technologies to address contributing factors, and develop process or operational strategies to mitigate remaining factors.

Advanced Algal Systems R&D Barriers and Challenges

Aft-A. Biomass Availability and Cost: The lack of sufficient data on potential price, location, seasonality, environmental sustainability, quality, and quantity of available algal biomass feedstock creates uncertainty. Established biomass production history is required to understand feedstock supply risks. Reliable, consistent, and sustainable biomass supply is needed to reduce financial, technical, and operational risk to downstream processes.

Aft-B. Sustainable Algae Production: The productivity, energy use, and environmental effects of algae production and harvest systems have not been comprehensively addressed. New production technologies for algae cultivation are needed to lower the resource intensity of algae production.

Aft-C. Biomass Genetics and Development: The productivity and robustness of algae strains against such factors as temperature, seasonality, predation, and competition could be improved by selection, screening, breeding, mixing cultures, and/or genetic engineering. These approaches require extensive ecological, genetic, and biochemical information. In addition, any genetically modified organisms deployed commercially will also require regulatory approval by the appropriate federal, state, and local government agencies.

Aft-D. Sustainable Harvesting: Harvesting and dewatering technologies can be costly and energy- and resource-intensive. Algae biomass harvesting technology must be scalable with low energy intensity and high reliability. After removal of algae biomass, recycle of harvest water and media can be important.

Aft-E. Algal Biomass Characterization, Quality, and Monitoring: Physical, chemical, biological, and post-harvest physiological variations in algae are important. The fundamental components (lipids, carbohydrates, and proteins) of algal biomass vary greatly within strains, among strains, and in comparison to plants. A better understanding of the effects of the high variability in feedstock characteristics on biorefinery operations and performance is needed. Standard procedures to reliably and reproducibly quantify biomass components from algae and to close mass balances are necessary.

Aft-F. Algae Storage Systems: Characterization and analysis of different algae storage methods and strategies are needed to define storage requirements for seasonal variances or design flexibility. These storage methods should preserve harvested algal biomass or biofuel intermediates to maintain product yield over time. Energy use and sustainability implications of storage methods must also be understood.

Aft-G. Algal Feedstock Material Properties: Data on algal feedstock quality and physical property characteristics in relation to conversion process performance characteristics are limited. Methods and instruments for measuring physical, chemical, and biomechanical properties of biomass are needed.

Aft-H. Integration: Integration of co-located inoculation, cultivation, primary harvest, concentration, and preprocessing systems is challenging and requires interdisciplinary expertise. In addition, the potential for co-location with other related bioenergy technologies to improve balance of plant costs and logistics may be important.

Aft-I. Algal Feedstock On-Farm Preprocessing: After cultivation and harvesting, algal biomass may require processing or fractionation into lipids, bio-oils, carbohydrates, and/or proteins before these individual components can be converted into the desired fuel and/or products. Integration of pre-processing with algae cultivation poses challenges in operations, as well as energy efficiency and capital costs.

Aft-J. Resource Recapture and Recycle: Residual materials remaining after preprocessing and/or residual processing may contain valuable nitrogen, phosphorus, carbon, or micronutrients, all of which can displace a portion of fresh fertilizer inputs in upstream cultivation. The recapture of these resources from harvest and logistics process waste streams may pose separation challenges, and the recovered materials may not be in biologically available chemical forms. In closed-loop systems, inhibitory compounds may also accumulate.

Conversion R&D Barriers and Challenges

Ct-A. Defining Metrics around Feedstock Quality: Discrete and quantifiable metrics relating feedstock quality characteristics (e.g., ash content, ash speciation, particle size distribution, particle shape distribution, surface roughness, concentration of contaminant species, and organic impurities) and their impact on conversion performance (e.g., yield, catalyst deactivation, and organism toxicity) is necessary. At a minimum, the upper and lower bounds of feedstock quality characteristics that can result in economically viable convertibility need to be identified. End-to-end system throughput analysis is needed to quantify trade-offs between cheaper, lower-quality feedstocks (including blends) and biofuel and coproduct yields, maintenance cycles, and costs.

Ct-B. Efficient Preprocessing and Pretreatment: Trade-off analysis is necessary to optimize pretreatment and preprocessing steps with further downstream processes. This relates to barrier Ct-A above, with respect to identifying unit operations that can mitigate against particular contaminant species or lower-quality feedstocks, as additional unit operations increase the overall energy intensity, capital expenditure, and costs of biomass processes.

If/when pretreatment and preprocessing strategies are not available, then it may be necessary to further develop more robust downstream processes. Particle and reaction modeling, experimental evaluation, and concurrent development of subsequent conversion processes is needed to assess key parameters including sugar yields, lignin convertibility, pretreatment reactor uptime, and heat and mass transfer properties.

Ct-C. Process Development for Conversion of Lignin: Converting lignin into value-added products has been a widespread challenge associated with the development of lignocellulosic biofuels. Despite constituting between 15% and 40% of biomass by weight, it is generally burned in biorefineries for relatively low-value heat and power. The structural complexity of the lignin polymer makes it notoriously difficult to extract greater value from lignin. Recent advances in molecular understanding of this complex polymer point to the potential for lignin to play an increasingly important role in the development of biofuel and value-added bioproducts. In addition to fully deconstructing lignin into low molecular weight compounds, strategies for the synthesis of high-performance products that maintain some structural properties of native lignin (e.g., carbon fibers, resins, and foams) afford additional avenues for deriving value from lignin.

Ct-D. Advanced Bioprocess Development: Increasing titer, rates, and yields of bioproducts through metabolic engineering and fermentation processing improvements is critical to lowering the costs of fuels and chemicals produced from biomass. In addition, continuous or semi-continuous bioprocessing strategies can reduce the needed capital and operating costs through increased productivity and reduced organism propagation costs, compared to traditional batch fermentation. Unique challenges exist to develop robust organisms or biocatalysts, along with advanced bioreactors, that can achieve long efficacy times. Real-time measurement and adaptive control strategies that are tailored to the particular organism, catalyst, and/or product are also necessary.

Ct-E. Improving Catalyst Lifetime: There is a need both for catalysts that are more tolerant of lower-quality feedstocks and for pretreatment and separation processes that eliminate contaminant species from intermediate solutions. Developing these processes should be coupled with efforts to obtain a better understanding of the causes of catalyst poisoning and deactivation, specifically in bio-based processes, to more efficiently target contaminants. In addition to developing more robust catalysts and processes, there is a need to decrease the energy intensity and material demand required for catalyst regeneration.

Ct-F. Increasing the Yield from Catalytic Processes: There is also a need to identify catalysts and process conditions that increase overall yield. This can be accomplished by direct improvements to catalyst performance that minimize the loss of carbon and by process improvements that decrease the formation of undesirable intermediates. A better understanding of catalytic active sites and reaction mechanisms, across both low- and high-temperature processes, can be obtained through advanced characterization techniques. Advanced reactor modeling and developing bio-oil characterization techniques can help identify reaction conditions that impact the ratio of different intermediates in high-temperature processes that typically produce a wide range of intermediates. Challenges associated with hydrogen sourcing, cost, and utilization also must be addressed to enable the development of more efficient, highly active, selective, and durable catalysts. Current methods for generating hydrogen are not cost-efficient at the scale envisioned for most biorefineries, and a reliance on externally produced hydrogen contributes to operating costs.

Ct-G. Decreasing the Time and Cost to Develop Novel Industrially Relevant Catalysts: Emerging technologies and processes may require the design and synthesis of novel catalysts. Existing catalysts may also contain materials that become cost-prohibitive when used at larger scales. Researchers need to be able to respond to these needs and identify and synthesize novel catalysts that meet cost and performance targets on an industrially relevant time scale. Understanding the trade-offs between catalyst material and catalyst performance requires detailed information on material costs, as well as robust computational models that can predict reaction mechanisms and catalyst and reactor performance under different operating conditions.

Ct-H. Gas Fermentation Development: There are unique challenges that must be overcome for gaseous feedstocks to be processed viably. Gas fermentations inherently require continuous modes of operation, as gas storage/recycle loops are largely infeasible (due to costs of compression and capital equipment sizing). Gas streams from biomass can be challenging to transition from gas to liquid, so novel reactors and/or process configurations to maximize the single-pass conversion of these feedstocks are needed.

Ct-I. Development of Processes Capable of Processing High-Moisture Feedstocks in Addition to Conventional Anaerobic Digestion: Anaerobic digestion is a widely practiced method for waste management and biogas production from high-moisture feedstocks (sludge from wastewater treatment plants, manure, food waste, and other fractions of municipal solid waste). High-temperature processes, such as gasification or pyrolysis, are inherently inefficient, as a high amount of energy is expended in heating or drying. Additionally, anaerobic digestion requires significant feedstock volumes to offset the high capital costs. Furthermore, anaerobic digestion typically only converts 50% of the organic matter, which results in a significant disposal problem for waste producers. Developing systems with lower capital costs that can convert higher fractions of the waste and that can produce liquid fuels and bioproducts present unique opportunities. A number of unique challenges exist to developing these processes, including identifying individual organisms or consortia of organisms that can produce high quantities of product (e.g. organic acids), developing methods for continuous separations of these products, and testing and developing stable systems (>2,000 hours).

Ct-J. Identification and Evaluation of Potential Bioproducts: To more efficiently realize the full value of biomass feedstocks, conversion processes need to integrate bioproduct production with that of drop-in fuels. Experimental methods and computational analysis to link intermediates from specific processes with potential products (both drop-in replacements and novel molecules that utilize the unique characteristics of biomass feedstocks) need to be developed. Once potential structures are identified, novel molecules will also require high-throughput screening tools to characterize and optimize them for properties that are advantageous to the molecules already used in industrial processes. Metrics and protocols for high-throughput screening will need to be standardized. Additional analysis of molecules and their properties including machine learning will be required to develop a larger database of predictive structure-function relationships that will reduce development time. Experimental methods for comparing both drop-in replacements and novel products with existing products to assess purity and performance will need to be developed.

Ct-K. Developing Methods for Bioproduct Production: Bioproducts will be introduced into existing markets that typically have high requirements for purity. Additional separation steps or other unit operations may need to be added to existing processes to ensure that bioproducts are recovered with industrially relevant specs. Additionally, properties present in molecules that are tested at the lab and bench scale must be understood fundamentally to enable a transfer to larger scales. Because production processes for many bio-based molecules cannot be scaled rapidly, this increases the risk associated with testing bio-based replacements in formulas.

Ct-L. Decreasing Development Time for Industrially Relevant Microorganisms: Bringing a new biologically produced molecule to market using current biomanufacturing practices can cost more than $150 million dollars and take more than 10 years. While individual companies have made some progress on reducing this time and cost, they often rely on proprietary methods that are specific to individual organisms and product targets, limiting broad applicability. To decrease this time and cost for the bioeconomy as a whole, publicly available new biomanufacturing techniques are needed, as well as new microbial host organisms with improved industrial properties. Central to this challenge is the development of new microbiology techniques in conjunction with databases and machine learning methods to enable better, more automated design of bioprocesses with predictable performance and scaling, as well as significantly increased conversion efficiency. To be truly industrially useful, these efforts must be integrated into a methodology that enables faster and more efficient development cycles.

Ct-M. Current Reactors not Designed to Handle Harsh Conditions Inherent to Converting Biomass Feedstock: Current reactors must be improved to cost-effectively deliver an environment in which catalysts and organisms can be most efficient, including the ability to withstand highly corrosive bio-oil and cost-effectively handle harsh pretreatment conditions for low-temperature deconstruction. This involves developing reactors with cost-effective materials that are optimized for process conditions. In addition, it is currently difficult to precisely control many biological and other processes. New techniques, instruments, and methods are needed to maximize process operation efficiency.

Ct-N. Multiscale Computational Framework toward Accelerating Technology Development: Predictive models need to be integrated with experimental data and verified at multiple scales to accelerate technology development. Models must be developed for translating material behavior and performance from atomic scales to industrially relevant reactor scales, and developing methods to reduce technology uncertainty and time requirements for the scale-up of advanced conversion technologies.

Ct-O. Selective Separations of Organic Species: Separation of organic species in biomass processes for upgrading to final fuel and bioproduct molecules has high energy requirements. Desirable compounds are often closely related structurally to undesired intermediates. These separations require a more thorough compilation of physical properties for complex mixtures of process intermediates, and better modeling methods to improve predictions of acid-water interactions. Low-cost purification technologies need to be developed to remove other organic contaminants and provide concentrated, clean intermediates from which biofuels and bio-based chemicals can be manufactured.

Ct-P. Selective Separations of Inorganic Contaminants: Inorganic species found in feedstocks or in intermediate streams can be incompatible with conversion processes, as they can result in issues such as catalyst poisoning and side reactions. Additionally, their presence in product streams can lead to off-specification products that are unacceptable for fuels or bioproducts. Effective mitigation strategies, such as treatments that can applied for their selective removal, are needed. Absent these mitigation strategies, these feedstocks may be limited to conversion processes that are insensitive to these feedstock compositions.

Advanced Development and Optimization Barriers and Challenges

ADO-A. Process Integration: The concept of an integrated biorefinery encompasses a wide range of process steps and technical issues. These include collecting, storing, transporting, and processing diverse feedstocks and moving feedstocks through multiple complex conversion subsystems to produce fuel and/or product outputs. The technical performance and operational behavior of unit operations during individual component verification could be significantly different when the same set of individual unit operations are assembled together to form an integrated system. Researching that systems perform as designed when integrated is a challenging and time-consuming process. Understanding process integration is essential to (1) characterize the interactions between unit operations, (2) identify the impacts of inhibitors and contaminants on processing systems, (3) generate predictive engineering models to guide process optimization and scale-up efforts and develop process control methodologies, and (4) devise equipment design parameters and operational considerations to improve reliability of operations and increase on-stream performance of equipment.

ADO-B. Feedstock Supply Chain Infrastructure: The supply chain infrastructure capable of handling large volumes of highly variable feedstocks is limited. Variable composition, geographical diversity, and diverse physical properties (such as particle size, bulk density, moisture content, and inorganic species present) impact supply chain costs. Feedstock infrastructure, such as handling and storage facilities, must also meet existing construction, safety, and fire codes, which, in most cases, were not developed for large-scale lignocellulosic biomass operations.

ADO-C. Codes, Standards, and Approval for Use: New biofuels and biofuel blends are not available in sufficient volumes required to perform product certification prescreening requirements. Biofuels and biofuel blends must comply with federal, state, and regional regulations before being approved and certified for end use. Codes and standards are adopted by federal, state, and regional jurisdictions to ensure product safety and reliability, and reduce liability.

ADO-D. Technology Uncertainty of Integration and Scaling: Unit operations proven at small scale under laboratory conditions need to be scaled up and assembled together in an integrated setup or pilot-scale facility to verify process performance. Determining scaling factors for industry best practice of stepwise scaling needs to be based on credible data from operations at the appropriate level of process integration and scale. This enables subsequent robust, full integration and development of equipment specifications for commercial application.

ADO-E. Co-Development of Fuels and Engines: There are numerous pathways for producing biofuel blendstocks, but current efforts target engines and vehicles that are on the road today. At the same time, most advanced engine development efforts are constrained by the fuels in the market today. Co-development of fuels and engines has the potential to increase vehicle engine efficiency, improve fuel economy, and reduce emissions. Realizing these benefits requires improved understanding of what fuel properties are needed to optimize advanced engine performance and what desirable properties can be provided by biofuel blendstocks.

ADO-F. First-of-a-Kind Technology Development: Studies have shown that the number and complexity of new process steps implemented in first-of-a-kind technology projects are a strong predictor of the challenges to be encountered with reliable performance and operations. Understanding relationships between and within unit operations is critical to inform R&D gaps and for further technology development. Heat and mass balances, along with other implications, including characterization of bioprocessing streams, are not likely to be well understood in new technologies. Additional challenges can be attributed to handling of non-pristine solids; buildup of impurities in process recycle streams; degradation of chemical or catalyst performance; inorganic species in the process streams, char, and slag buildup; and abrasion, fouling, and corrosion of plant equipment. Furthermore, reliable databases providing interactions of various feedstocks with processing equipment, efficient handling of feedstocks, and predictive methods for feedstock properties are not readily available.

ADO-G. Co-Processing with Petroleum Refineries: Bio-oil and bio-intermediates are comprised of components and mixtures different than those found in petroleum refineries, and knowledge on the influence of bio-intermediates blending with petroleum processing is still in the developmental stage. Material characteristics such as physiochemical properties, reactivities, and compatibilities of bio-intermediates with petroleum derivatives need to be well understood. To be accepted for co-processing, petroleum refineries need to understand how a bio-oil or bio-intermediates will perform when integrated into existing operations. The results will be useful to address the GHG effects of co-processed fuel products.

ADO-H. Materials Compatibility, and Equipment Design and Optimization: Current equipment may not be designed to handle the harsh conditions inherent to biofuels production; for example, they may be incompatible with highly corrosive and erosive nature of feedstocks, biomass, and bio-intermediates. Methods are needed to identify appropriate construction materials and establish process optimization conditions to co-develop equipment. In addition, procedures employed from current refinery practices must be extended to include characteristics of biomass and bio-intermediates.

Strategic Analysis and Crosscutting Sustainability Barriers and Challenges

At-A. Analysis to Inform Strategic Direction: Analysis is needed to better understand factors influencing the growth and development of the bioenergy and bioproducts industries, identify the most impactful R&D strategies, define BETO goals, and inform BETO strategic direction.

At-B. Analytical Tools and Capabilities for System-Level Analysis: High-quality analytical tools and models are needed to better understand bioenergy supply chain systems, linkages, and dependencies. Models need to be developed and refined to reflect new knowledge, scientific breakthroughs, and enable informed decision-making. Improvements in model components and linkages are necessary to improve utility, consistency, and reliability.

At-C. Data Availability across the Supply Chain: Understanding the biomass-to-bioenergy supply chain and its economic, environmental, and other impacts requires complete and comparable data. Filling data gaps and improving data accessibility would improve efforts to understand all relevant dimensions of bioenergy and bioproducts production and use and inform model development.

At-D. Identifying New Market Opportunities for Bioenergy and Bioproducts: Biofuels and bioproducts can potentially offer performance advantages relative to other technology options, and they can also provide unique solutions in certain sectors that have limited energy alternatives, such as aviation and marine. Ongoing, forward-looking analyses are needed to identify these opportunities so that R&D priorities can be adjusted appropriately.

At-E. Quantification of Economic, Environmental, and Other Benefits and Costs: When the economic, environmental, and other benefits of bioenergy and bioproducts are uncertain or not quantified, it is difficult to define their value proposition and to make comparisons among energy alternatives. This makes bioenergy technologies less likely to be adopted by the private sector. It is necessary to quantify both the costs and benefits so that synergies can be enhanced, trade-offs can be minimized, and R&D can be directed toward more sustainable outcomes. Furthermore, analyses must use transparent and defensible assumptions to be properly interpreted and to drive toward agreement across the stakeholder community.

At-F. Science-Based Methods for Improving Sustainability: Once the costs and benefits of a given bioenergy or bioproduct system are evaluated, solutions must be developed that improve system performance and economic, environmental, and/or social outcomes. Furthermore, as bioenergy and bioproduct production from cellulosic, algal, and waste feedstocks is relatively new, few "best practices" are defined for all components of the supply chain. This requires research and development of science-based tools and improved practices in a variety of contexts to accelerate learning and continuous improvement across the emerging bioeconomy.

At-G. Social Acceptance and Stakeholder Involvement: The successful transfer of bioenergy technologies to the private sector will require significant involvement from landowners, technology developers, local communities, environmental organizations, regulatory bodies, and the broader public. Improved mechanisms are needed to better inform and involve these stakeholders in developing context-specific goals that consider local opportunities and constraints.

At-H. Consensus, Data, and Proactive Strategies for Improving Land-Use Management: The limitations of existing data sources to capture the dynamic state of land use and management, as well as an incomplete understanding of the drivers of land-use and land-management changes, have undermined efforts to assess the environmental and social effects of bioenergy production and consumption. Science-based, multi-stakeholder strategies are needed to integrate bioenergy with agricultural and forestry systems in a way that reduces wastes, maintains crop yields, enhances resiliency, and supports multiple ecosystem services.