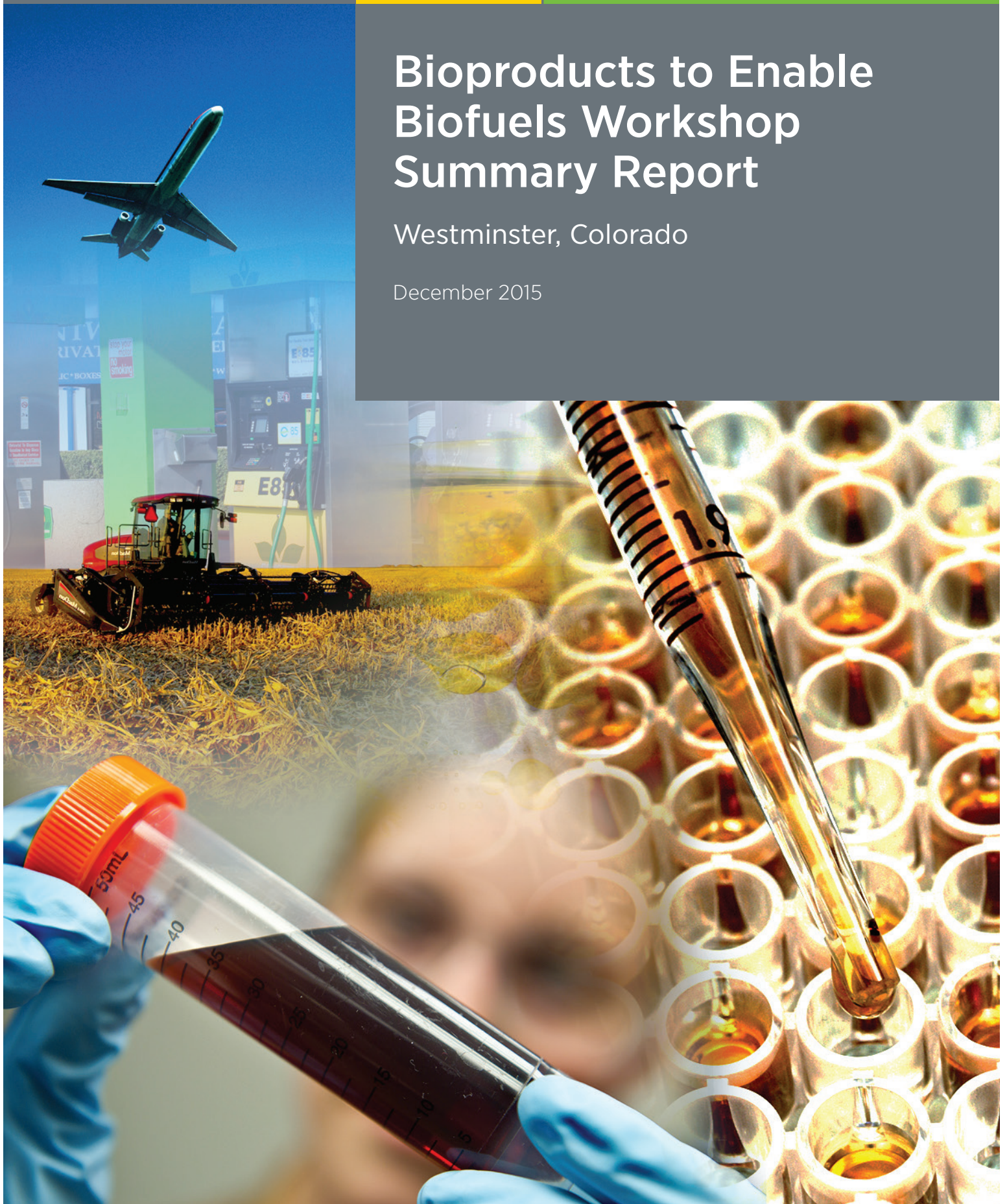


Bioproducts to Enable Biofuels Workshop Summary Report

Westminster, Colorado

December 2015



Summary Report from the July 16, 2015,
Bioproducts to Enable Biofuels Workshop in Westminster, Colorado

Workshop and Summary Report sponsored by the U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
Bioenergy Technologies Office

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Preface

The U.S. Department of Energy's (DOE's) Office of Energy Efficiency and Renewable Energy (EERE) invests in a diverse portfolio of energy technologies to achieve a stronger economy, a cleaner environment, and a more secure energy future for America.

This report summarizes the results of a public workshop sponsored by DOE/EERE in Westminster, Colorado, on July 16, 2015. The views and opinions of the workshop attendees, as summarized in this document, do not necessarily reflect those of the United States government or any agency thereof, nor do their employees make any warranty, expressed or implied, or assume any liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represent that its use would not infringe upon privately owned rights.

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Introduction

On July 16, 2015, the U.S. Department of Energy’s (DOE’s) Office of Energy Efficiency and Renewable Energy Bioenergy Technologies Office (BETO; the Office) hosted a workshop in Westminster, Colorado, to discuss research and development (R&D) opportunities related to the co-production of bioproducts alongside biofuels. Ninety-four stakeholders from industry, national laboratories, government agencies, research institutions, and universities provided information on economic and R&D challenges associated with the current state of bioproduct production technologies (Fig. 1).

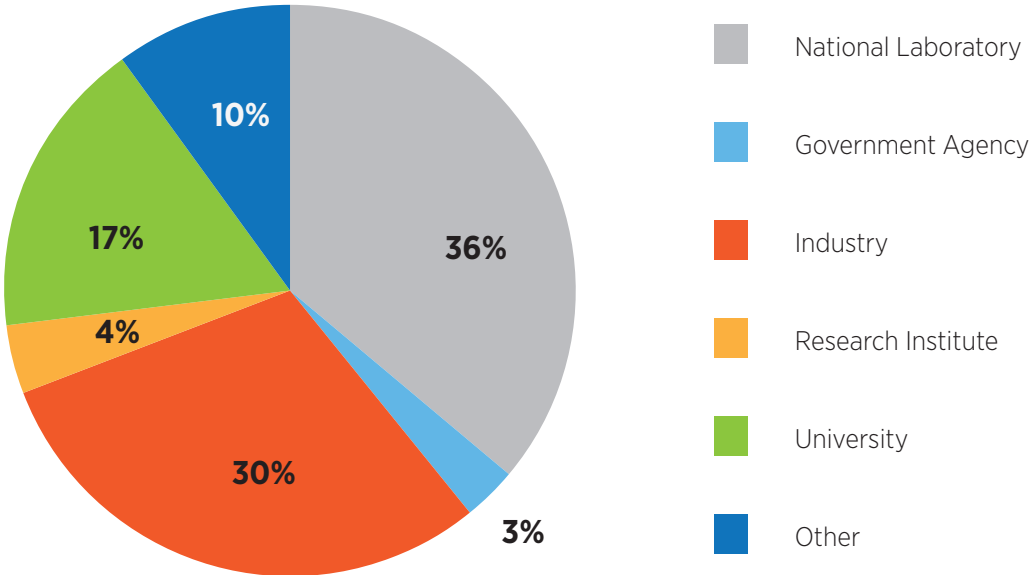


Figure 1. Breakdown by sector of session attendees at the Bioproducts to Enable Biofuels Workshop

Purpose of the Workshop

BETO funds research, development, and demonstration of a variety of technologies and processes to support domestic production of biofuels, bio-based chemicals, and biopower. BETO focuses on reducing technology risks from feedstock supply and logistics through biorefinery technologies to enable industry investment in technology deployment at scale. BETO has a successful track record of supporting R&D in cellulosic ethanol technologies, many of which are currently being deployed and commercialized. As cellulosic ethanol technologies mature, BETO has shifted its R&D support towards advancing technologies to create products that serve as drop-in replacements for fuels, such as gasoline, diesel, and jet fuel, and chemicals that can be substituted for their fossil-derived counterparts or which may more easily be produced from biomass.

BETO has the goal of funding research that supports the production of biomass-derived hydrocarbon fuels at the minimum fuel selling price (MFSP) of \$3/gallon gasoline equivalent (gge). One approach that BETO has taken

is to focus on conversion pathways that exclusively produce biofuels (A of Fig. 2 below). This approach was highly successful for producing cellulosic ethanol. With BETO’s current focus on hydrocarbon fuels, it might be necessary to examine other strategies (B and C of Fig. 2 below). Strategies B and C capitalize on revenue from co-products as part of a strategy for producing cost-competitive biofuels. There are many technology pathways that could be used to produce hydrocarbon biofuels, but many of them would require the co-production of value-added chemicals and products to produce cost-competitive fuels in the near-term (B and C in Fig. 2 for example pathways). For example, National Renewable Energy Laboratory has demonstrated that when producing a hydrocarbon fuel via an enzymatic hydrolysis followed by biological upgrading conversion pathway (the conversion pathway that was highly successful for producing cellulosic ethanol)—the sale of lignin-derived coproduct (such as adipic acid) will be necessary to achieve a MFSP of \$3/gge for a gasoline and diesel blendstock (Fig. 3).

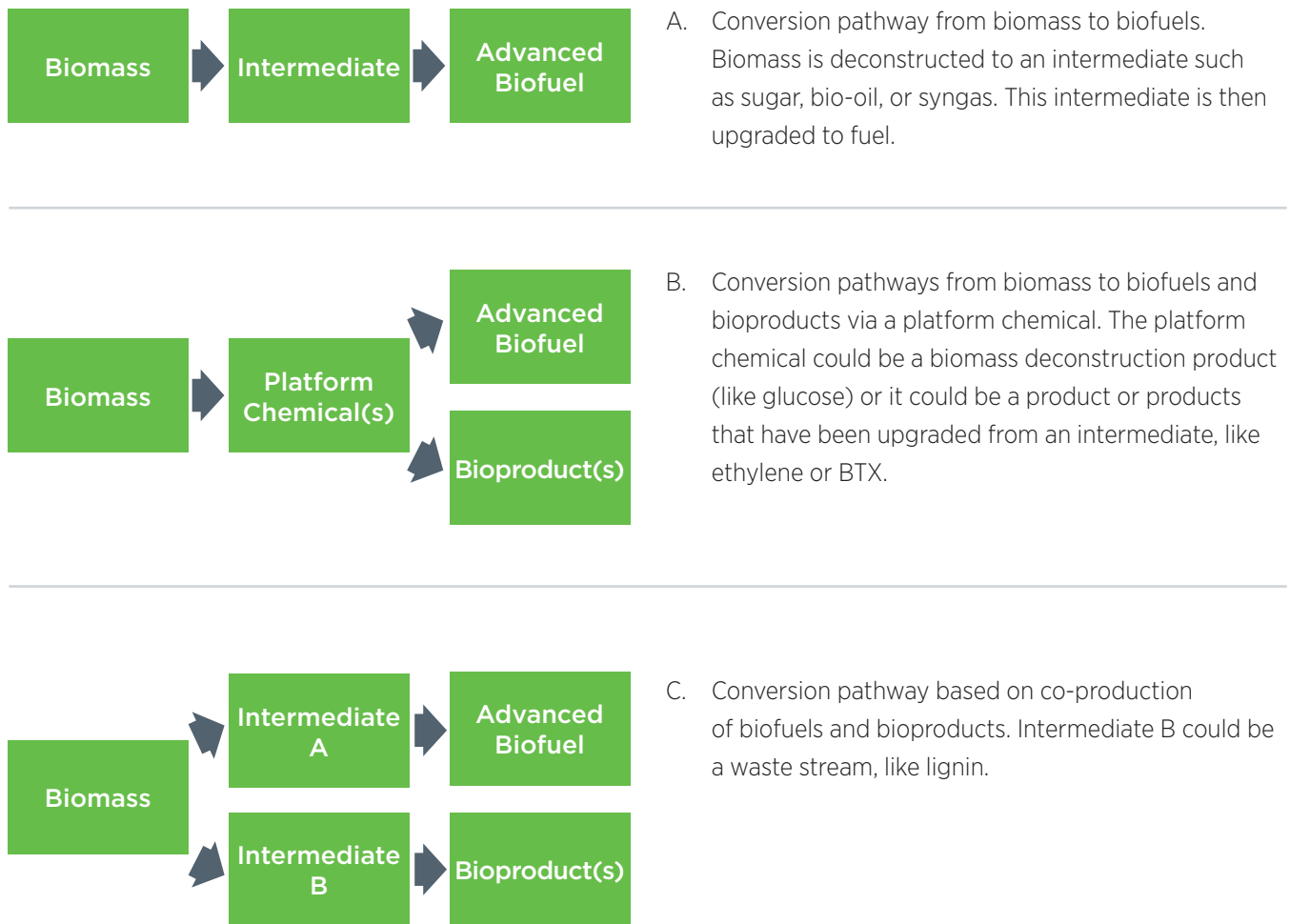


Figure 2. Pathways to producing biofuels.

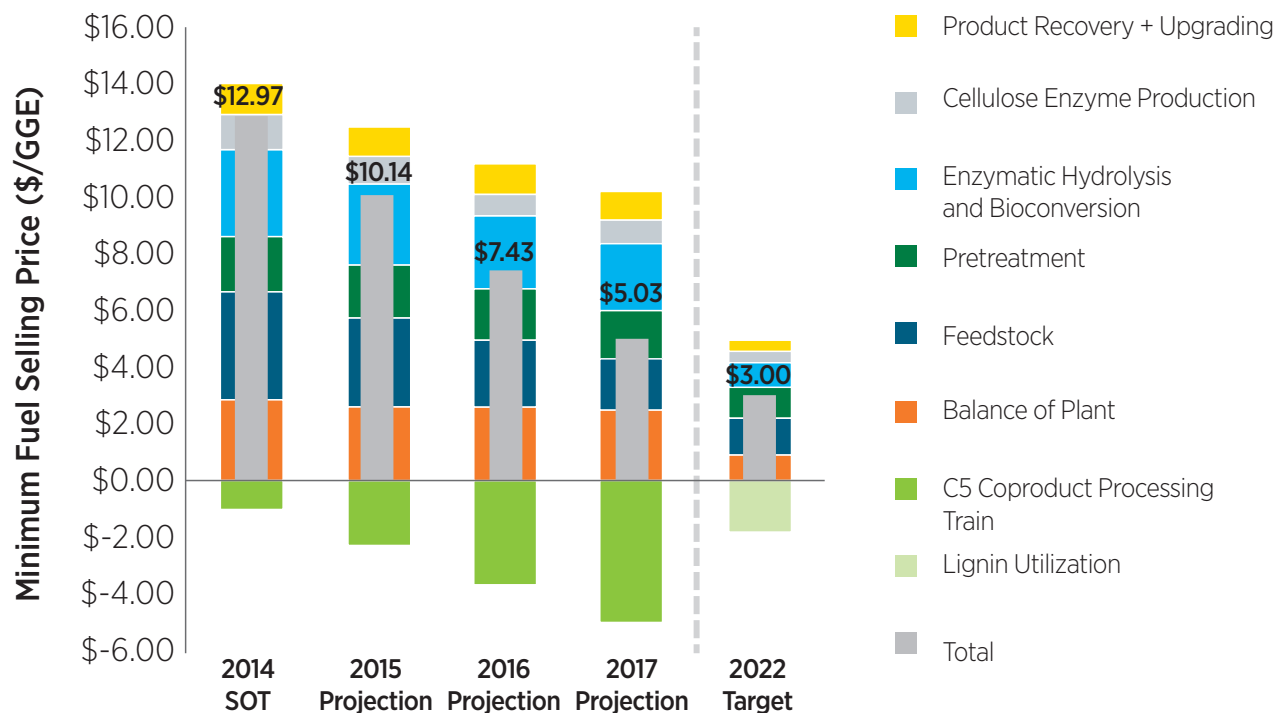


Figure 3. Waterfall chart showing the MFSP of a hydrocarbon fuel produced via an enzymatic hydrolysis followed by bioconversion pathway. To reach an MFSP of \$3/gge, the lignin waste stream must be converted to a value-added product (in this case, adipic acid). SOT = state of technology. *Source: BETO Multi-Year Program Plan, March 2015, p. 2-80.*¹

The strategy of producing bioproducts alongside biofuels is analogous to the approach of the petrochemical industry to producing fuels and chemicals. A major advantage of the petroleum industry is that its product slate is flexible and can be tuned to market demand. Furthermore, the petroleum industry takes advantage of the high margins commanded by chemicals as compared to fuels (Fig. 4). As illustrated in Figure 4, approximately 75% of the volume of a barrel of crude oil goes towards making fuels, corresponding to \$935 billion in revenue. In contrast, only 16% of a barrel of oil goes towards making petrochemicals; despite the much smaller volume, these chemicals produce almost as much revenue as fuels (\$812 billion in revenue for chemicals). *To have a positive return on investment (ROI) for a biorefinery that generates biofuels that are cost competitive with their petroleum-derived counterparts, it could be necessary to flexibly co-produce bioproducts that can be sold at higher margins.*

¹ U.S. Department of Energy Bioenergy Technologies Office, “Bioenergy Technologies Office Multi-Year Program Plan, March 2015,” http://energy.gov/sites/prod/files/2015/04/f22/mypp_beto_march2015.pdf.

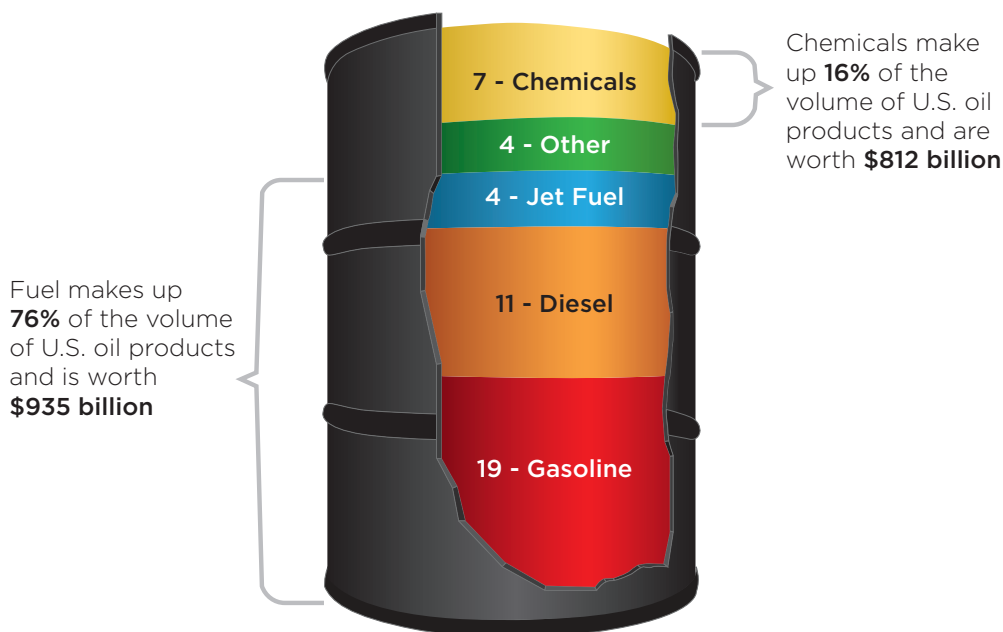


Figure 4. Products and revenue from a barrel of oil. *Source: Bloomberg New Energy Finance, U.S. Energy Information Administration, American Chemical Council*

The purpose of this workshop was to get stakeholder input about the potential role of bioproducts in the biofuels industry. BETO seeks to enable biorefineries that can profit from cost-competitive hydrocarbon biofuels, and there is mounting evidence that production of bioproducts could enable this goal. Particularly, BETO was interested in learning the following:

- In what ways can the production of bioproducts enable the production of biofuels?
- Will coproducing products be necessary to ensure the economic feasibility of advanced biofuel production?
- Are there common intermediates that are best suited for making products and fuels?
- Are there platform technologies that are best for making products and fuels?

The answers that stakeholders provided to these questions will help BETO shape its research funding strategy.

Workshop Concept and Process

The Bioproducts to Enable Biofuels Workshop gathered 94 knowledgeable stakeholders for a day of discussion on the current state of technology and barriers to commercialization of biological and chemical processes that convert biomass to biofuels and bioproducts. These stakeholders represent a variety of affiliations, including industry, national laboratories, government agencies, research institutions, and universities. The day began with two keynote addresses from BETO to provide attendees with necessary context to the Office’s mission and the goals of the workshop. Two presentations from external stakeholders followed, setting the stage for workshop participation. Three sets of facilitated breakout sessions allowed attendees to provide input on a variety of topics. Finally, at the conclusion of the day, representatives from each breakout session reported out on their findings. See Appendix A for a detailed agenda.

Workshop Keynotes

Jonathan Male, Director, BETO

Jonathan Male, BETO Director, provided an overview of the Office and the technologies it supports through R&D efforts. BETO is tasked with developing and transforming renewable biomass resources into commercially viable, high-performance biofuels and bioproducts through targeted research, development, demonstration, and market transformation.

The 2013 BETO Project Peer Review Steering Committee Final Report suggested that BETO take a more active role in bioproduct research. The Steering Committee said that, “Given the wide array of potential co-products, it will be critical for the Office to focus on co-products that match specific biofuels pathways” (2013 Peer Review Report²). To that end, this workshop is the most recent in a line of activities BETO has participated in on the topic of bioproducts.

Kevin Craig, Conversion Program Manager, BETO

The Conversion Program Manager, Kevin Craig, spoke on how the Conversion Program’s R&D efforts have been guided by taking products into consideration. The strategic goal of the Conversion Program is to develop commercially viable technologies for converting feedstocks via biological and chemical routes energy-dense, fungible, finished liquid fuels, such as renewable gasoline, jet fuel, and diesel, as well as biochemicals and biopower.

BETO can invest in several types of strategies as the Conversion Program moves into the bioproduct space to encourage bioproduct production. BETO could invest in products that enable and support existing biorefineries (bio-gas conversion, acid pre-treated lignin), or that enable the operation of future biorefineries based on current research projections (alkaline lignins). BETO could also invest in products that are manufactured in standalone facilities. These standalone facilities would produce products that enable the construction of supply systems/depots and would be intended to help de-risk biorefineries through lessons learned.

Claire Curry, Advanced Transport Associate, Bloomberg New Energy Finance

Claire Curry, an Advanced Transport Associate from Bloomberg New Energy Finance, then gave the first keynote on how bioproducts and biochemicals can influence the biofuels industry going forward. Bloomberg’s Advanced Transport Division researches innovations in vehicles, fuels, and infrastructure, and provides both domestic and international market projections for biofuels and bioproducts.

Ms. Curry began by discussing the evolution of biofuels business models (Fig. 5). When the second-generation biofuel industry began (circa 2006), it centered on an integrated biorefinery concept, attempting to mimic the successful petroleum refinery model, which produces a range of products to optimize production economics and feedstock use. Unfortunately, the production of multiple products made it difficult for banks and venture capital firms to understand the opportunity, and by 2008, start-up biofuel companies had shifted away from this multi-product approach to a one-product model focusing on simpler molecules and commoditized products. The single-product

² U.S. Department of Energy Bioenergy Technologies Office, “2013 Peer Review Report,” February 2014, http://energy.gov/sites/prod/files/2014/03/f14/2013_peer_review.pdf.

model was intended to make the industry more attractive for investors, but a struggle to sign off-take agreements for these products and achieve differentiation with their competitors failed to give them success. By 2012, biofuel start-ups had begun to attract strategic partners that demanded specific biofuel and biochemical products and were willing to pay R&D costs, thereby driving product, end-market differentiation, and a renaissance of the biorefinery model.

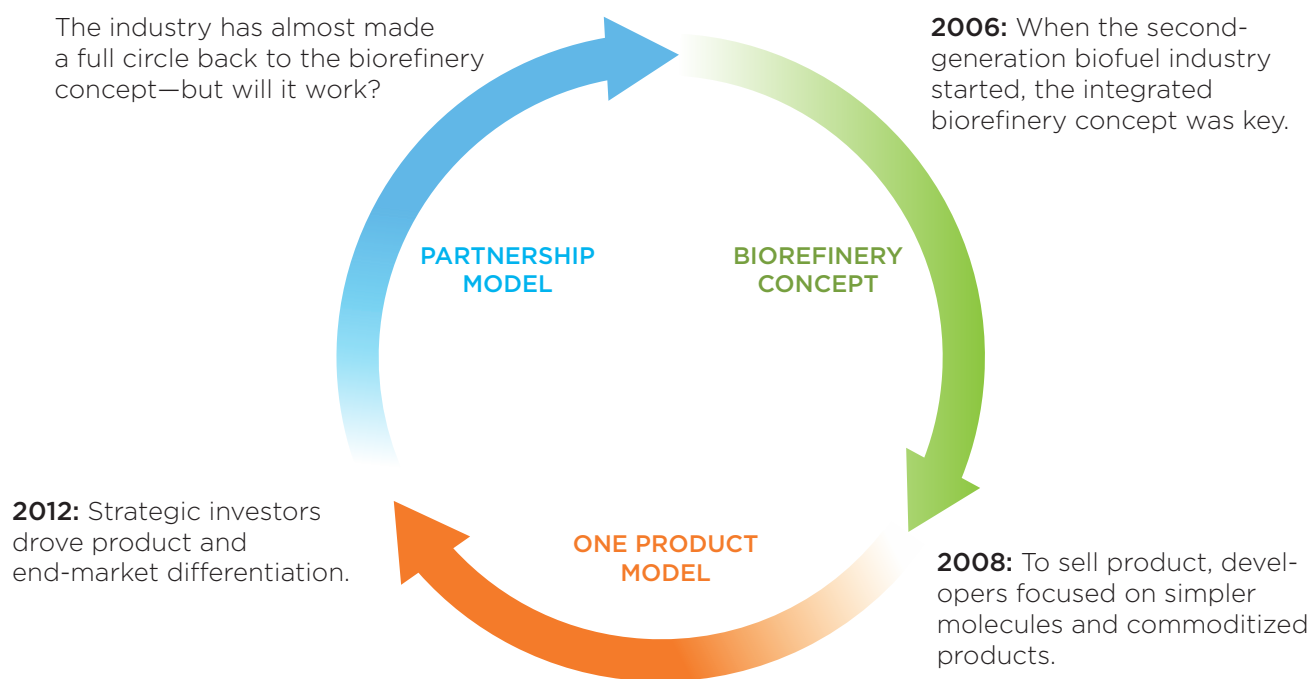


Figure 5. The evolution of biofuels business models. *Source: Bloomberg New Energy Finance.*

Selecting a bioproduct for production typically involves considering two questions: (1) does the product have a high price point? and (2) are there available industry partners who will invest in the product due to factors such as a nice market or an environmental agenda?

Ms. Curry presented two constructs for determining which biomass-derived chemicals will be most attractive to the market: (1) high price points and (2) the concerns of industry partners (Fig. 6). High price points can be attractive, but it is imperative to look at their origins. For example, is the high price point due to a complex production process? Is that production linked to the price of oil and, as a result, subject to price fluctuations and market shocks? Ms. Curry pointed out that succinic acid is an ideal target: it has a relatively small market (50,000 tonne), and it is expensive to make from petroleum. As such, if petroleum prices drop, the succinic acid price would not.

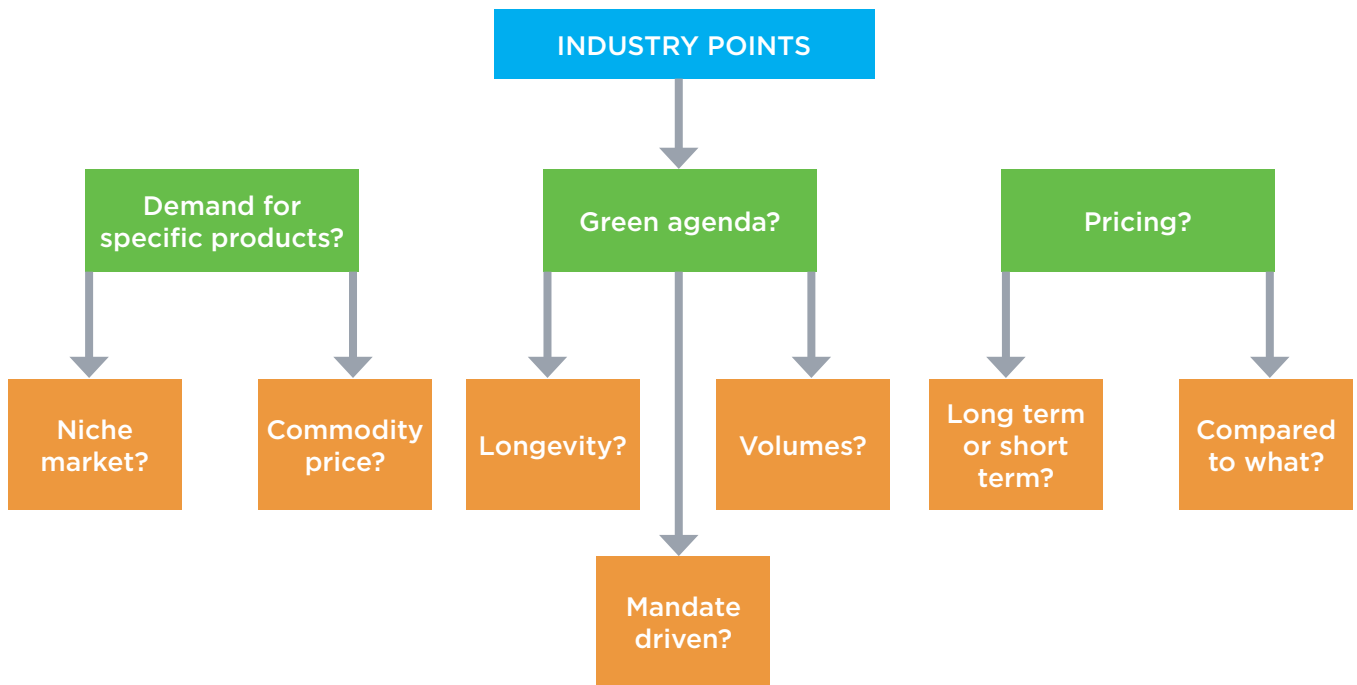
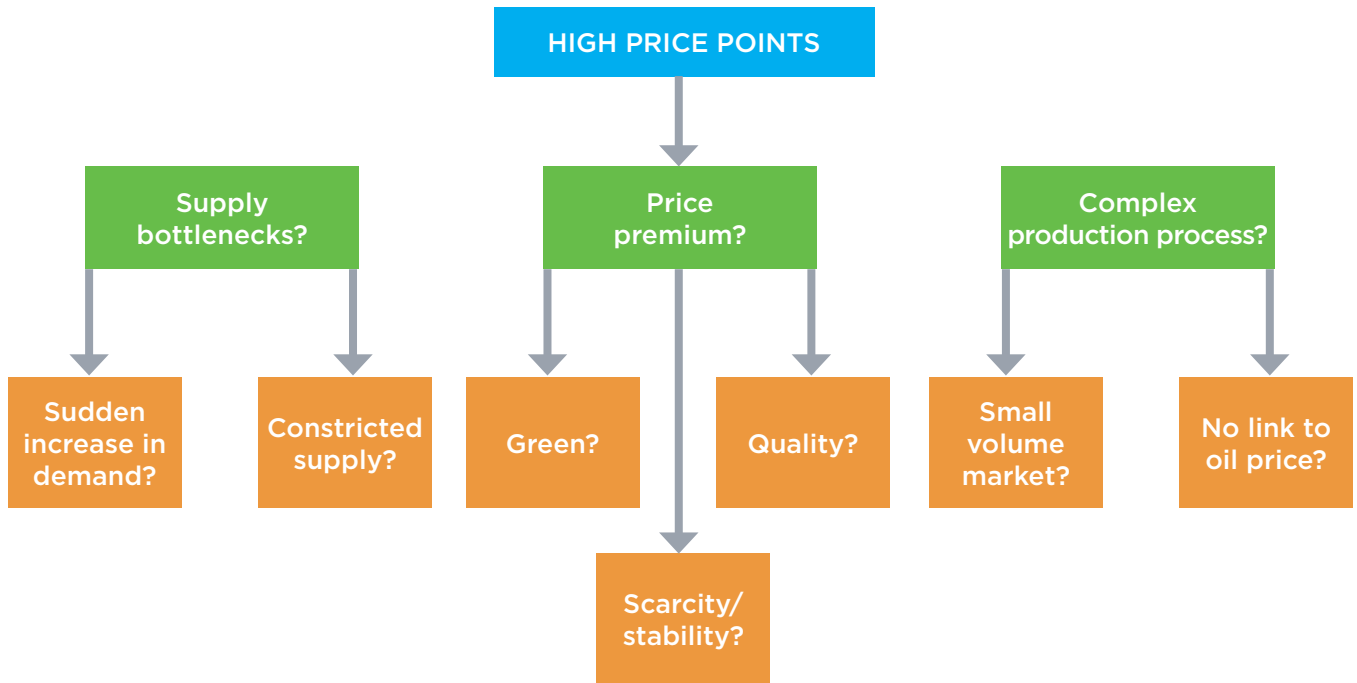


Figure 6. Considerations when targeting bioproducts. *Source: Bloomberg New Energy Finance.*

Ms. Curry pointed out that fuels continue to be the most attractive long-term market. It is unclear how products like biochemicals will help commercialize biofuels. A focus on bioproducts will either distract from biofuels development and impede commercialization, or their production will bridge the gap between the current high costs of producing biofuels and the cost they can sell for, thus ultimately bringing advanced biofuels to commercialization. However, even if their production does help to commercialize biofuels, it would be on a delayed timeline that would be of no help to governments aiming to meet current 2020/2022 biofuel mandates.

David Sudolsky, President and CEO, Anellotech

David Sudolsky, President and CEO of Anellotech, gave the second keynote on an industrial perspective on bioproducts. Anellotech develops bio-based aromatic chemicals that act as direct substitutes for their petroleum-based equivalents in several consumer products. Anellotech expects its Catalytic Fast Pyrolysis technology, which converts biomass to these chemicals in a single processing step, to reach commercial scale by 2019.

Although Anellotech originally focused on fuel production, they eventually found that it was easier to attract investors with bioproducts than biofuels. Because fuel refineries and chemical plants are long-term investments that require stable economics to be viable, it was important to identify strategies to minimize costs.

Mr. Sudolsky said that bio-based chemicals can enable the production of biofuels, but this process will require smart management by interested companies. Leveraging potential partnerships (both people and facilities) elsewhere in the field will be crucial to successful efforts, in addition to being smart about market dynamics. When planning market entry, companies should start at the commercial level and then work backwards. Early development and commercialization of relevant technologies can help run companies down the cost-experience curve, leading to earlier cost-competitive processes.

Breakout Session Structure

Following the keynote speakers, the full group of workshop participants took part in a facilitated discussion session where the participants were asked a series of general questions about how bioproducts can enable biofuels. Participants responded to these questions to the full group of workshop attendees.

The morning session questions provided a high-level overview of some of the challenges and opportunities for bioproducts as related to the production of biofuels. In the afternoon, participants split into two breakout groups to discuss topics pertaining to the four outlined sessions listed as follows (Appendix A):

- Economic drivers—economic considerations
- Economic drivers—target selection
- Challenges and barriers to efficient biological conversion
- Challenges and barriers to efficient chemical conversion.

Each breakout session lasted two hours and took a deeper dive into challenges and opportunities for bioproducts, using the question list provided in Appendix B. Participant answers were compiled using notecards and then sorted based upon similar answers. Groups of 3–5 participants discussed each question and shifted halfway through

the breakout session to ensure that participants from different fields had the opportunity to share their opinions with one another. The discussions were captured in spreadsheets and notes, and participant input is reflected in the session summaries below. At the end of the day, selected members from each breakout session reported out the highlights of their respective sessions to the attendees at large.

Workshop Participant Responses

Large Breakout Session: How Bioproducts Can Enable Biofuels

In what ways can the production of bioproducts enable the production of biofuels?

Attendees suggested numerous ways that the production of bioproducts enable the production of biofuels. Responses from attendees ranged from broad comments on how bioproducts can help strengthen the larger concept of a bioeconomy to more specific comments on how bioproducts can improve market potential for existing and new biorefineries.

Ways that bioproducts enable biofuels: bolstering the bioeconomy

Many participants said that any activity that bolstered the bioeconomy would have a positive impact on biofuels production. *The production of bioproducts relies on much of the same feedstocks, infrastructure, feedstock commoditization, and technologies central to biofuels production.* Participants emphasized that the knowledge gained from producing bioproducts can be transferred to biofuels. Bioproducts producers in attendance noted that they use bioproducts as a means to develop the platform technologies that can potentially lead to fuels. National laboratory researchers noted that there are major challenges associated with biomass feedstocks and any lessons learned will be useful, regardless if the final products are biofuels or bioproducts.

Products may also fill gaps in the fuel production process by providing the opportunity to research processes that are otherwise too risky to invest in at a full scale. Research on bioproducts can reveal many new or unexplored processing options for biofuels production. Currently, due to the relatively low profit margin associated with fuel production, researchers typically focus on minimizing costs of known unit operations within a biomass conversion pathway in an effort to produce cost-competitive biofuels. Pursuing products that command higher margins allows researchers more freedom to explore conversion technologies that would be cost prohibitive for fuels applications. Once these technologies are demonstrated for bioproducts, cost-reduction research (i.e., improved efficiency, cheaper alternative materials, etc.) would be worth exploring for biofuels applications. *These technologies may greatly improve biofuels production and, once proven for bioproducts applications, could greatly improve biofuels production.* A specific example is biomass pretreatment. Some pretreatment technologies are not investigated because they are considered prohibitively expensive; however, they could potentially produce cleaner materials for conversion and reduce conversion and separations costs. Bioproducts provide a venue to explore high-risk, high-reward solutions that could be applicable to biofuels.

Ways that bioproducts enable biofuels: market entry

Some participants noted that due to market factors, *they are seeing a transition to products as the primary output of many production streams, with fuel becoming the co-product.* Entry into bioproduct markets can be easier than entry into fuels markets, and profits from bioproduct production may be able to offset current fuel-related costs, which could provide fuel producers time for processes to become more efficient.

Many participants emphasized the need for replicating the successful business model of the petrochemical industry. Enabling a diverse product slate from a biorefinery, especially by valorizing materials that are currently waste products, can substantially reduce risks associated with early biofuel plants and biorefineries. Production of bioproducts can also significantly de-risk the upstream infrastructure and processes needed for biofuels by providing an increased economic incentive for the construction of pioneer biorefineries.

Additional thoughts from participants on the question of ways that bioproducts enable the production of biofuels included the following:

- Participants pointed out that production of petrochemicals is a very energy-intensive industry. As such, a focus on producing chemicals from biomass is still a focus on energy.
- Representatives from larger companies noted that sustainability is important to many corporations. Corporations will be interested in purchasing products that demonstrate improved greenhouse gas (GHG) profiles. Biofuels are one option, but bioproducts offer many more options for corporations to support the bioeconomy.

Will coproducing products be necessary to ensure the economic feasibility of advanced biofuel production? If so, how? If not, why not?

Most participants said that products would be necessary to ensure the economic feasibility of advanced biofuels. As suggested above, the economic advantages of bioproduct production are some of the most compelling reasons that fuel producers would want to explore coproduction. Participants suggested that moving into product and chemical markets would also allow biorefineries to mitigate economic risk by pursuing a higher-value product and may make them more attractive to potential investors.

Additional thoughts from participants on the question of coproducts ensuring the economic feasibility of fuel production included the following:

- One participant noted that worldwide chemicals are growing at 1%–1.5% per year, faster than the global gross domestic product. The fuels market is shrinking, particularly the gasoline portion (diesel and jet fuel less so). In addition, in the fuels market, biofuels producers are competing against petroleum-derived fuels producers who are using depreciated capital.
- Technology developed for bioproducts will be applicable to biofuels production; improved technologies could lead to reducing the cost of biofuel production by improving feedstock logistics, improving solids handling and feeding, developing new enzymes and novel deconstruction technologies, and other possible improvements. These technical improvements will result in lower capital cost of future biofuel plants, and time to nameplate capacity will be reduced.
- Initial investments in bioproduct plants may also give the industry more time to allow the public to better understand the industry. Maintaining positive public perception, which helps to define policy, has been a challenge for in the past.

Although most workshop participants enthusiastically supported bioproducts as a strategy to enable biofuels, some expressed concerns about this strategy. A focus on bioproducts detracts from a research focus on biofuels, and as a result, it might slow down the research progress necessary to achieve cost-competitive biofuels production. Some workshop participants expressed limited concern over abandoning fuels entirely as product markets become highly profitable. Also, while investors may find attractive the potential short-term profits that can be gained by switching away from fuels, participants expressed concern over regaining the added capital costs associated with production changes. In this case, *the amount of incremental value gained from going to fuels relative to the capital expense required may not be sufficiently viable.*

Finally, some attendees noted that there are technical barriers to embracing a biorefinery model: for instance, oil refineries have an outlet for a product that, due to market oversaturation or product specification issues, has been produced in excess by adding it to the fuel supply. With biofuels, this strategy would be difficult, if not impossible. Therefore, some participants were concerned that producing chemicals alongside fuels might not enable the economic feasibility of biorefineries.

If bioproducts are coproduced with biofuels, how much carbon should be devoted to fuels versus products?

Participants were asked the question above in two sessions, both in the large group discussion and in the chemical R&D session. *The general consensus was that having any metric that requires a specific amount of carbon to go to fuels would greatly impede R&D and commercialization because it would stop companies from being able to adapt to market fluctuations.* Participants said they prefer letting market value drive the specific amounts, with the understanding that the amount is likely a sliding scale that will change over time. Industrial participants noted that some companies are seeing that biofuel is becoming the by-product and products are becoming the primary output. They suggested that government funding agencies be open to the idea that liquid fuel may not be the focus of a refinery if the commercial economics are reasonable.

Small Breakout Sessions 1 and 2: Economic Drivers for Bioproducts

For the first set of afternoon sessions, participants were invited to self-select one of two sessions related to the economics of bioproduct production. Participants from industry were generally encouraged to attend the “economic considerations” session, while researchers were encouraged to attend the “target selection” session at their own discretion. Participants in each session were asked slightly different questions (Appendix B) based on the suggested participant demographics.

Both sessions began by asking participants to read through a list of potential criteria to be considered when selecting target products (Appendix B) and select what they believe to be the top five most important from the list. Participants could write in additional factors not included on the list. At the end of the breakout session, participants returned their surveys to workshop facilitators. The results are summarized on the following page:

Provided Answers	Percentage of returned surveys in which criterion was ranked as the most important*	Percentage of returned surveys in which criterion was ranked in the participant's top 5
Product could serve as a building block/platform chemical for a biorefinery	24%	72%
Product is produced via a conversion technology that is broadly applicable to multiple products and/or fuels	14%	70%
Product is a direct substitute for an existing petrochemical	10%	56%
Product can be produced with an improved GHG profile over its petrochemical counterpart (life-cycle analysis)	10%	54%
Product commands a large market	12%	52%
Product has unique, desirable characteristics	0%	40%
Product can be produced from waste streams from fuel production	2%	36%
Product is synthesized via known technology	6%	26%
Product is part of a niche market	2%	12%
Product is a novel molecule (i.e., not a direct replacement for a petrochemical)	0%	10%
Other (see below)	20%	48%

*Because participants were allowed to write in their own answers and rank them, the total percentage will not add up to 100.

Table 1. Survey responses “Criteria to consider when selecting target bioproducts”

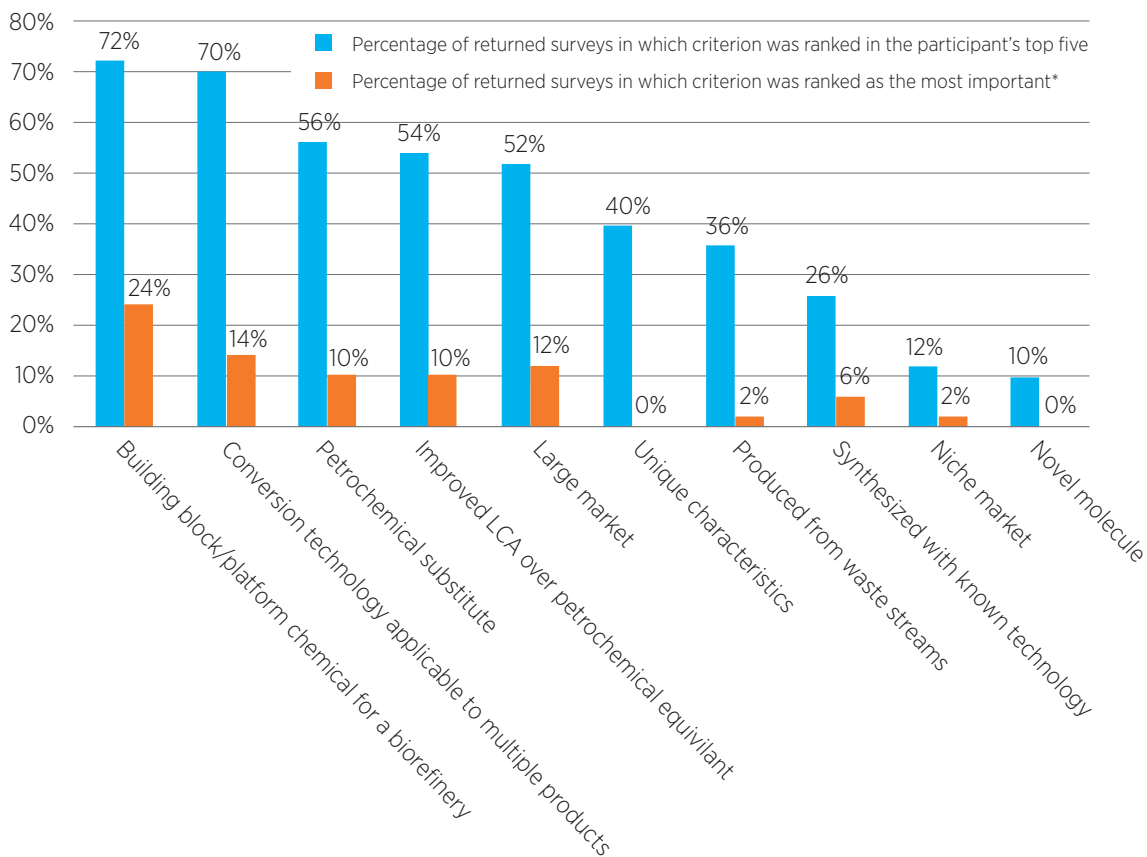


Figure 7. Survey responses “Criteria to consider when selecting target bioproducts”; LCA = life-cycle analysis.

The following are additional criteria that at least one participant suggested (the number of times each criterion was suggested appears in parentheses):

- The product has the potential to be profitable (14)
- The product stream is easy to separate (2)
- The product utilizes an available feedstock (2)
- The product is part of a single production platform that could be used for multiple products (1)
- The product addresses an existing problem (1)
- The product has the ability to overcome regulatory hurdles (1)
- The product provides strategic partnership opportunities (1)
- The product is atom efficient (1)
- The product can be produced at a large scale in existing production facilities (1).

Factors Affecting Bioproduct Selection

What factors should be considered when selecting bioproducts for production?

Several groups emphasized the fact that *products should be produced by technologies that are broadly applicable to multiple products, including fuels and chemicals*, based on data that already exist. Additional suggestions included the following:

- The product should act as a building block for other products.
- The product should be simple and potentially start with an easy target platform chemical to reduce risk.
- Technologies should utilize multiple feedstocks including waste streams from other processes.
- The product should be produced using existing fuel infrastructure.
- The economic viability of the target product should be considered which may lead to targeting either a large or niche market.
- The product should be an environmentally favorable direct replacement for a petroleum product.
- There should be consumer demand and market pull for products.
- The sustainability of a potential product should be considered (e.g., GHG reduction potential, water use, and carbon footprint).
- The product should be economically viable (the ability to attract financing from outside sources and to affect job creation).
- The product should have the potential to provide functional improvement over a traditional petroleum-based product.

What are the major challenges and barriers to biofuel and bioproduct co-production (non-R&D)?

Attendees identified numerous non-R&D challenges to developing bioproducts and biofuels. Challenges specific to R&D were addressed in the afternoon session on R&D challenges (see page 17). Many of the challenges identified in this session roughly fit into two categories: regulatory hurdles and market acceptance.

Regulatory hurdles: New bioproducts face a complicated regulatory landscape before reaching the market. Attendees noted that if a bioproduct is not produced by an identical process to the equivalent molecule it is replacing, it could be regulated differently by the U.S. Environmental Protection Agency (EPA). Workshop participants suggested that DOE work closely with EPA in anticipation of this challenge. In addition to federal regulations, there will be state- and municipality-level regulations that DOE may also need to account for. The corn-ethanol industry previously faced regulatory hurdles as it was sometimes unclear whether it was part of the food or chemical industry. There may be some lessons learned from this process that could apply to bioproducts.

Market acceptance: There was general agreement that market acceptance plays a critical role in the success of bioproducts. There are several main challenges to gaining market acceptance, including the following:

- Economic viability of the potential product—so it can exist without subsidies (high associated capital costs and low ROIs; is the product more expensive when compared to a traditional petroleum-based product?)

- Public perception of bioproducts—lack of consumer education, questions of purity, durability; additionally, educating the public about the differences between different labels associated with bioproducts (bio-based vs. biodegradable)
- Timescale required to bring products to market (including time required to set regulatory requirements in place)
- Ability to build on the existing market
- Requirements to use specific feedstocks
- Need to be in the right place on the supply/experience curve
- Risk profile of a technology—challenging to lower it.

Hydrogen sourcing: Workshop participants disagreed over whether or not obtaining hydrogen for reductions should be seen as a barrier. Some participants said they thought the current cost of constructing a co-located hydrogen plant is prohibitive for product production, while others thought costs were sufficiently low. Since bioproducts can retain some oxygen functionality whereas hydrocarbon fuels cannot, the cost of hydrogen is likely more of a concern for the biofuels industry.

Specific Bioproduct Target Chemicals

What are some bio-derived platform chemicals that could be used for both fuels and products synthesis?

Chemicals with similar structures to those needed for fuels would be a good starting point when selecting potential target chemicals. Focusing first on structures that the existing fuel production system generates and then selecting specific chemicals has the advantage of ensuring that the bioproducts of choice really are enabling existing fuel systems. The product of choice will differ depending on existing refinery operations.

Participants suggested that ethanol be used as a platform chemical to make both fuels and chemicals. Many specific chemicals and chemical groups were also proposed, including levulinic acid, BTX (benzene, toluene, and xylenes), methane, ethylene, methoxyphenols, olefins, paraffins, HMF, isoprenoids, higher alcohols, and fatty acids. In general, choosing products that do not have high purity standards would also decrease potential regulatory challenges.

Which products are most amenable to co-production alongside fuels?

When considering products that may be most amenable to co-production alongside fuels, participants named animal feed, lignin derivatives, niche products, and products containing oxygen, such as polyols, acids, aldehydes, and alcohols. Some participants stressed that it is important to fit the product to an existing market, rather than choosing a target product ahead of time and then trying to generate the market.

Which products would be best produced at a standalone facility?

In contrast, participants also considered optimal products for standalone facilities, or facilities without the capabilities for the co-production of fuels. Based on these criteria, most standalone facilities were only considered viable in specialized situations, including the following:

- Niche markets not tied to oil/gas (pharmaceutical and nutraceutical markets where contamination is a concern)
- Co-location of the plant with a specialized source of biomass (a challenge in this case would be the feedstock yield).

Participants emphasized that any production facility was unlikely to make just one product and that residual streams could always constitute a secondary source of revenue.

What current fossil-sourced products are good candidates for renewable replacement?

Products that can capitalize on “green” marketing (e.g., cosmetics) may be able to capture a unique market share if they were bio-based. Other general products that were suggested were petrochemical building blocks, products that include oxygen, plastics, lubricants, surfactants. More specific chemicals and chemical groups that could be targeted included C5/C4 aldehydes, polyurethane, acrylonitrile, methane, styrene replacements, BPA (Bis-phenol A), benzene, and phosphorus compounds that can be used in lieu of halogen-based flame retardants.

Market Drivers for Bioproducts

What kinds of incentives would you need to encourage you to use cellulosic feedstocks (vs. starch-based sugars)?

Participants suggested specific incentives that would help encourage the use of cellulosic feedstocks:

- Renewable products standard similar to the Renewable Fuel Standard
- Tax credits
- A guaranteed off-take agreement
- Large grants targeted at R&D.

Participants also discussed additional incentives, such as those that lower the cost of feedstocks, thereby normalizing cellulosic sugars to starch-based sugars, and those that value the GHG reduction potential; however, some participants said that in general, incentives should only be available when the technology is closer to acceptance and not in an early phase. Technology needs to first prove that it is viable before incentives are introduced.

Sessions 3 and 4: Challenges and Barriers to Efficient Chemical and Biological Conversion

For these sessions, participants were allowed to self-select one of two breakout groups; one focusing on chemical conversion, and the second on biological conversion. Each group was asked a similar set of questions to provide input regarding their respective conversion technologies and associated challenges and barriers. The reason for separating these two groups was to allow for more focused discussion; however, in this report those results are combined below. Workshop participants identified key R&D challenges associated with bioproducts for both near term (< 5 years) and long term (> 5 years). Identifying broad-based technology platforms that require more R&D as well as concepts for targeting application-specific technical barriers and strategies for coproducing products alongside biofuels were also discussed.

Challenges Associated with Bioproducts

What are the near-term (< 5 years) and long-term (> 5 years) R&D challenges associated with bioproducts?

When asked to identify near-term R&D challenges associated with bioproducts, many technical process-related concerns were identified for both platforms, including the following:

- Challenges related to feedstocks (cost, purity, variability)
- Catalyst issues (cost, high yield vs. selectivity, reactions to feedstock variability)
- Robust reactor design
- Separations and purification (both upstream and downstream).

In addition to the general concerns, the biological R&D group discussed challenges related to fermentation (e.g., toxicity), and the development of a robust organism, and potential organism contamination.

Additional overarching challenges for both groups identified included the following:

- Risks associated with scale-up
- Process integration between biological and chemical methods
- Funding
- Pulling several modular developments together to improve the full production process.

For long-term R&D challenges associated with bioproducts, several short-term challenges were reiterated, and additional challenges included the following:

- Decentralized processing
- Technology transfer
- Market adjustments (dealing with variability and choosing which products to pursue going forward)
- Developing predictive trajectories for improvement and scalability
- Using real feedstocks over model feedstocks
- Overcoming challenges related to continuous processing.

It will become easier to recognize the challenges associated with producing bioproducts as markets expand. Participants mentioned obstacles—both technical and economic—that they expect to be significant in the next five years, based on the current state of technology. Both biological and chemical stakeholders identified technical processes as the primary initial challenges. These challenges included overcoming feedstock (e.g., cost, purity, and variability) and catalyst (e.g., cost and yield vs. selectivity) issues, designing more robust reactors, and dealing with separations and purification of both upstream and downstream processes. Participants in both groups suggested that separation technology is an area that could benefit highly from immediate attention. The biological group also identified many unique challenges related to fermentation, the development of a robust organism, and potential organism contamination. Overall process challenges include those associated with pulling several modular developments together to improve the full production process and integrating biological and chemical methods.

Other challenges may influence the progress of bioproduct R&D, but are not technical in nature. These include the risks associated with scaling up technology, and guaranteeing funding in a project's early stages.

When asked about challenges on a longer time horizon, participants reiterated many of the short-term challenges, but they said they assumed that some issues will be more significant as the market expands. Depending on how industry deals with these more immediate hurdles, producers will need to start adjusting to market variability and making additional decisions about which product streams to keep investing in and which to drop. Long-term financial support and continued access to capital for facilities will also depend on the state of the product market. As bioproducts become more common, they may also face a more complex regulatory landscape.

Many technical challenges are expected to be relevant in the short term as producers start to scale up, but difficulties associated with maintaining biomolecule functionality, the transition from model to real feedstocks, and the move into more decentralized and continuous processing models will become potential issues as technology matures. Establishing technology transfer between users will also become important to avoid repeated mistakes and encourage innovation. As more data on bioproduct production is generated, it will also become crucial to track success stories and develop models for scalability and improvement.

Additional Gaps in Research and Development

In order to address these R&D challenges, certain areas could use additional research now. Participants emphasized that technologies designed for petroleum feedstocks will not necessarily transfer to biomass-derived products. Participants suggested the following additional areas for further development:

- Deoxygenation reactions including hydrogenation, electrochemical reductions, and microbial reductions
- Chain elongation reactions
- Lignin utilization
- Super critical fluid or super critical CO₂ extraction of chemicals from algae
- Sugars to high-value products
- Develop methane utilizing organisms
- Atom-efficient reactions and atom-efficient target molecules (i.e., targets that maintain oxygen from biomass).

What platform technologies are best suited for making products to enable fuels? What broad-based technology platforms need more research and development?

Desirable platform molecules are those that can be converted to both fuels and products. Participants identified BTX as a good example of a product mixture that allows for the ability to transition from chemicals to fuels, as the same technology to produce the chemical is also used for fuel production. Other platform molecules identified included those amenable to chain elongation towards reaching diesel-range compounds. Others suggested lignin-derived platform chemicals, such as methoxyphenols. Participants noted that specialty chemicals are not ideal targets because the processes for converting biomass to these chemicals are not easily translatable to fuels.

Desirable Platform Molecules	Corresponding Platform Technology
Mixtures of compounds that could be used as fuels or products (e.g., BTX)	Fast pyrolysis and related technologies
Molecules that mimic existing biomass structure (e.g., methoxyphenols from lignin)	Biological and chemical upgrading of sugars
Molecules with functionality amenable to chain extension to the diesel range (C ₈ -C ₂₁)	Syngas upgrading

Table 2. Desirable platform molecules and corresponding platform technologies

Participants highlighted the importance of leveraging existing work. There has already been considerable R&D for biofuel technologies, and this platform development does not need to be reinvented. As such, participants advocated for research approaches that capitalize on existing biofuels conversion platforms. Participants also advocated for approaches that focused on conversion platforms that lead to bioproducts and that could be translated to biofuels when markets are amenable.

There was general agreement that almost every technology platform could use additional research. Petroleum-based technologies are not necessarily transferrable to biomass processes. Additional specific suggestions included the following:

- Catalyst design (activity, selectivity, stability)
- Reactor design
- Pretreatment
- Waste stream utilization
- Lignin conversion technology
- Reductions (cheaper sources of hydrogen, increased selectivity, biological reduction)
- Separations (both upstream and downstream)
- Clean fractionation
- Real-time process instrumentation and control
- Modeling capabilities (product and pathway viability predictions)
- Integration into the existing fuels infrastructure.

The biochemical platform group also discussed synthetic biology, as well as novel organism design using genetic tools and metabolic engineering to obtain higher yields and pathway transfer across microbes.

Robust data collection in the early stages of product development will help industry to improve processes and make quicker changes to optimize systems. More research is needed in current computational capabilities, both for predicting product and pathway viabilities and real-time process monitoring. Assuming that many bioproduct streams will be integrated into existing fuel production systems, it will be necessary to understand the challenges associated with this process.

Many technologies show potential for coproduction of products and fuels, but workshop participants said that most of these technologies needed additional research to reach their full potential. These include target organisms beyond yeast and *E. coli* (current downstream and upstream technologies are being catered to these organisms, which is creating a bottleneck for researchers), fermentation that takes place at an industrial scale, ways to mitigate the loss of CO₂ in glycolysis, and improved reactor designs that can accommodate waste streams.

What are the technical challenges unique to cellulosic feedstocks (vs. starch-based sugars)?

Finally, the chemical R&D session concluded with a closing discussion regarding the technical challenges unique to cellulosic feedstocks. Several participants noted that there is no equivalent to the corn lobby for cellulosic feedstocks, reducing the potential legislative pull associated with research on these feedstocks. Because of this, general feedstock handling and processing challenges such as transportation, variability, composition, availability, and process integration may be harder to address. Cellulosic feedstocks exhibit variable complexity with varying reactivity, and present challenges related to oxygen removal.

Concluding Remarks

DOE has a clear mandate to employ science and discovery that will reduce the United States' dependence on foreign petroleum but will also mitigate climate change associated with greenhouse gas emissions caused by the consumption of petroleum. Producing biofuels and bio-based chemicals will help fulfill this mandate by

- Developing the science and technology necessary to displace the entire barrel of oil, which includes products made from petroleum.
- Achieving the higher margins associated with chemicals, which will enable the bioproducts industry as a whole.
- Assisting U.S. industry by utilizing non-fossil-based feedstocks that are not subject to the price volatility associated with petroleum.

The focus of this workshop was to gather information from various stakeholders about how the production of bioproducts could enable the production of biofuels. Stakeholders emphasized several themes regarding producing bioproducts:

- The production of bioproducts relies on much of the same feedstocks, infrastructure, feedstock commoditization, and technologies central to biofuels production.
- The knowledge gained from producing bioproducts can be transferred to biofuels.
- To have a positive ROI for a biorefinery that generates biofuels that are cost-competitive with their petroleum-derived counterparts, it could be necessary to flexibly co-produce bioproducts that can be sold at higher margins.
- Any metric requiring a specific amount of carbon to go to fuels would greatly impede R&D and commercialization because it would stop companies from being able to adapt to market fluctuations.
- An ideal bioproduct should
 - Be an environmentally favorable direct replacement for a petroleum product
 - Act as a building block for other products and fuels
 - Capitalize on the inherent structure of biomass (i.e., retain oxygen and carbon in the final product).

DOE very much appreciates the input provided by industry, government, laboratory personnel, and academic researchers who made this report possible.

Appendix A: Workshop Agenda

Time	Event	Speaker
8:30 a.m.–8:35 a.m.	Welcome	Nichole Fitzgerald—Oak Ridge Institute for Science and Education Fellow, Thermochemical Conversion, U.S. Department of Energy, Bioenergy Technologies Office
8:35 a.m.–8:55 a.m.	Introduction to BETO and Expanding the Bioeconomy	Jonathan Male—Director, DOE BETO
8:55 a.m.–9:15 a.m.	Conversion R&D Strategic Goals: “Bioproducts that Enable Biofuels”	Kevin Craig—Program Manager, Conversion Technologies, DOE BETO
9:15 a.m.–9:45 a.m.	An Analysis Perspective of Bioproducts and Biofuels	Claire Curry—Advanced Transport Associate, Bloomberg New Energy Finance
9:45 a.m.–10:15 a.m.	An Industrial Perspective of Bioproducts and Biofuels	David Sudolsky—President and CEO, Anellotech, Inc.
10:15 a.m.–10:30 a.m.	Break	
10:30 a.m.–12:00 p.m.	Large Stakeholder Facilitated Breakout Sessions: Relationship Between Biofuels and Bioproducts	Facilitators: Roy Tiley and Ashley Rose—BCS, Incorporated
12:00 p.m.–1:00 p.m.	Lunch Break	
1:00 p.m.–2:30 p.m.	Parallel Stakeholder Facilitated Breakout Sessions (1 and 2): Economic Drivers	Room 1: Bioproduct Target Identification Room 2: Economic Consideration
2:30 p.m.–2:45 p.m.	Break	
2:45 p.m.–4:15 p.m.	Parallel Stakeholder Facilitated Breakout Sessions (3 and 4): R&D Challenges	Room 1: Producing Bioproducts via Biological Conversion of Sugars, Lignin, Syngas, and Other Intermediates: R&D Challenges Room 2: Producing Bioproducts via Chemical Conversion of Sugars, Lignin, Syngas, and Other Intermediates: R&D Challenges
4:15 p.m.–4:30 p.m.	Break	
4:30 p.m.–5:30 p.m.	Report Out from Breakout Sessions	Representatives from Each Session
5:30 p.m.–5:45 p.m.	Concluding Remarks	Kevin Craig

Appendix B: Workshop Questions

Questions

Large Group Discussion

- In what ways can the production of bioproducts enable the production of biofuels?
- Will coproducing products be necessary to ensure the economic feasibility of advanced biofuel production? If so, how? If not, why not?
- What platform technologies and/or platform molecules are best suited for making products to *enable* fuels? Consider products that are coproduced with fuels and platforms that can be easily tuned to produce fuels or chemicals.

Parallel Stakeholder Facilitated Breakout Sessions: Economic Drivers

Small Group Discussion—Economic Considerations

- What factors should be considered when selecting bioproducts for production? (see handout)
- What are the challenges to market acceptance of a bioproduct?
- If you were to produce bioproducts, what size market for those products would you target? Why? What is the minimum market volume that you will consider targeting?
- What kinds of incentives would you need to encourage you to use cellulosic feedstocks (vs. starch-based sugars)?

Small Group Discussion—Target Selection

- What factors should be considered when selecting bioproducts for production? (see handout)
- Which products are most amenable to co-production alongside fuels? Which products are best for a standalone facility? What are the challenges associated with each?
- What are some bio-derived platform chemicals that could be used for both fuels and products synthesis?

Parallel Stakeholder Facilitated Breakout Sessions: R&D Challenges

Small Group Discussion—Chemical R&D Challenges and Biological R&D Challenges

- What are the near term (< 5 years) R&D challenges associated with bioproducts? Long term (> 5 years)?
- What broad-based technology platforms need more research and development? (e.g., selective reductions)
- What are technical barriers and strategies for *coproducing* products *alongside* biofuels? Are there technical challenges associated with diverting biomass intermediate streams to fuels versus chemicals?

Questions

Small Group Discussion (continued)—What factors should be considered when selecting a product?

When the list is complete, please rank them in order of importance.

- The product is produced via a conversion technology that is broadly applicable to multiple products and/or fuels
 - The product could serve as a building block/platform chemical for a biorefinery
 - The product can be produced from waste streams from fuel production
 - The product is a direct substitute for an existing petrochemical
 - The product is a novel molecule (i.e., not a direct replacement for a petrochemical)
 - The product can be produced with an improved GHG profile over its petrochemical counterpart (life-cycle analysis)
 - The product commands a large market
 - The product is part of a niche market
 - The product has unique, desirable characteristics
 - The product is synthesized via known technology.
-

Appendix C: Abbreviations and Acronyms

BETO	Bioenergy Technologies Office
BTX	benzene, toluene, and xylenes
DOE	U.S. Department of Energy
EERE	Office of Energy Efficiency and Renewable Energy
EPA	U.S. Environmental Protection Agency
GGE	gallon gasoline equivalent
GHG	greenhouse gas
LCA	life-cycle assessment
MFSP	minimum fuel selling price
R&D	research and development
ROI	return on investment
SOT	state of technology

Appendix D: Related Links

Bioproducts to Enable Biofuels Workshop

energy.gov/eere/bioenergy/bioproducts-enable-biofuels-workshop-0

Bioenergy Technologies Office

bioenergy.energy.gov

Bioenergy Technologies Office Multi-Year Program Plan

energy.gov/eere/bioenergy/downloads/bioenergy-technologies-office-multi-year-program-plan-march-2015-update

Office of Energy Efficiency and Renewable Energy

energy.gov/eere/office-energy-efficiency-renewable-energy

U.S. Department of Energy

energy.gov

Appendix E: Workshop Participants

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