WASTE TO ENERGY

TECHNOLOGY AREA

CONTENTS

INTRODUCTION

In the Waste-to-Energy (WTE) session, four external experts from industry and academia reviewed a total of nine projects.

This review addressed a total U.S. Department of Energy (DOE) investment value of approximately $18,733,224, which represents approximately 3% of the Bioenergy Technologies Office (BETO or the Office) portfolio reviewed during the 2017 Project Peer Review. During the Project Peer Review meeting, the principal investigator (PI) for each project was given between 15 to 30 minutes (depending on the project's funding level and relative importance to achieving BETO goals) to deliver a presentation and respond to questions from the Review Panel.

The Review Panel evaluated and scored projects for their project approach, technical progress and accomplishments, relevance to BETO goals, and future plans. This section of the report contains the results of the project review, including full scoring information for each project, summary comments from each reviewer, and any public response provided by the PI. This section also includes overview information on the WTE Technology Area, full scoring results and analysis, the Review Panel's summary report, and BETO's programmatic response.

The WTE Technology Area review had several BETO contributors. Andrea Bailey was responsible for all aspects of review planning and implementation, and David Babson was responsible for session facilitation.

WTE OVERVIEW

Wastes present a unique set of challenges for conversion processes, and BETO is exploring conversion possibilities at a wide variety of technology readiness levels (TRLs). Municipal, industrial, and agricultural wastes—as well as gaseous wastes, including carbon-rich industrial emissions, stranded natural gas, biogas, and even low-concentration carbon oxides recoverable from environmental systems (atmosphere or aquatic systems)—are potentially high-impact resources for the domestic production of fuels, products, heat, and electricity. Unlike traditional terrestrial bioenergy crops or algal biomass, waste resources are generated continuously as a byproduct of human activity. Established costs for managing wastes and mitigating associated harms present unique opportunities to avoid such costs and harms while generating valuable fuel, energy, and products.

Identified wastes and waste streams are broadly diverse and heterogenous. Given waste's inherent diversity and heterogeneity, distributed accumulation, and regulated and varied management requirements, one cannot adequately equate waste management and conversion technologies to other biorefining or biofuel production systems. For these reasons, BETO has begun considering the challenges and opportunities associated with waste feedstock, conversion, and advanced development and optimization independently. BETO discusses and considers waste valorization and management technologies separately in order to promote appropriately tuned technologies and design strategies for managing diverse waste inputs and for addressing unique challenges not encountered during traditional biomass handling. This approach provides an opportunity for better strategic planning and more useful, targeted research and development (R&D) investments in this space.

BETO is considering hydrothermal processing techniques as a more established conversion technology option. These efforts have benefited from prior funding under BETO's Advanced Algal Systems and Conversion R&D Program Areas. Research indicates that these and related technologies could process diverse blends of wet waste feedstocks, offering potential for widespread deployment. BETO's hydrothermal liquefaction efforts so far represent only a small part of the possibilities in this area; supercritical water also offers intriguing options, as do other fluids at high temperature and pressure, such as carbon dioxide (CO_2).

Several other conversion technologies are under investigation for both wet and gaseous waste feedstocks. Anaerobic digestion (AD)—a series of biological steps where microorganisms break down organic material in an oxygen-free setting to produce biogas—has the potential to become a widely used bioconversion process. Similarly, arrested methanogenesis, anaerobic membrane reactors, and various pre- and post-treatment strategies all appear to have promise. In terms of gaseous resources, thermochemical, biochemical, and electrochemical strategies all have some merit, as do various combinations of the three. It seems clear that exploring a broad range of possibilities, followed by a rigorous down-selection process, has a good chance of producing market-relevant platforms.

WTE REVIEW PANEL

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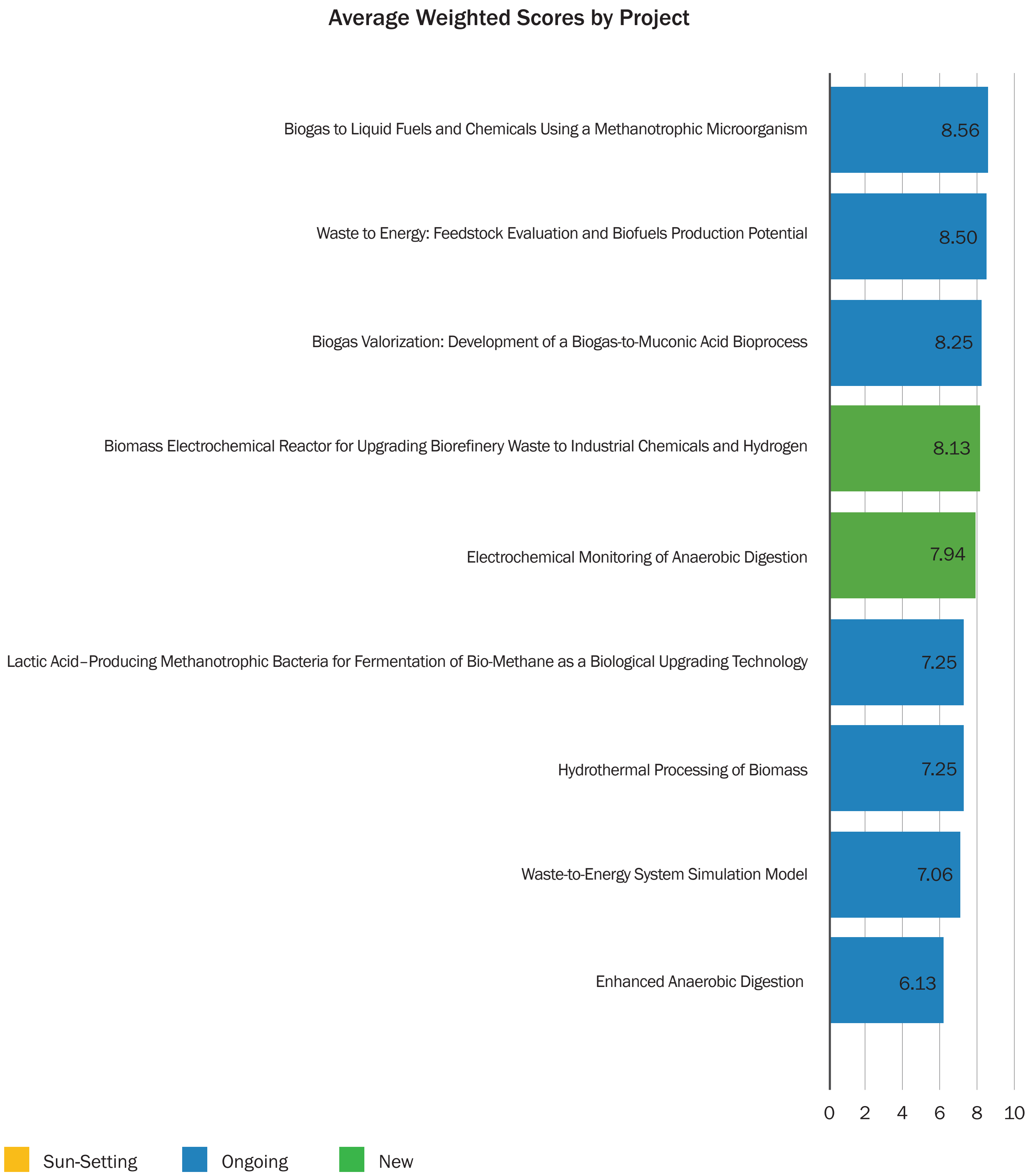
TECHNOLOGY AREA SCORE RESULTS



WTE REVIEW PANEL SUMMARY REPORT

Prepared by the WTE Review Panel

Introduction

This report is intended to provide high-level, general comments to the BETO program managers to guide and help them focus their WTE activities and increase the return on the public investment. This report does not intend to reconcile the opinions of the individual reviewers nor to discuss in detail specific projects; it aims to capture general themes, ideas, and observations and, where relevant, highlight different views. References to specific projects are present when the consideration has relevance for the whole programmatic area. Detailed project comments, especially those that are technical in nature and address specific issues of individual projects, are in the individual project reviews. The individual project reviews are and should remain the primary reference in judging the individual projects.

WTE is a relatively new area for BETO. As such, it includes projects that originally may have been part of other programmatic areas. It is the unanimous opinion of the Review Panel that the introduction of the WTE Technology Area is consistent with BETO's larger mission and is a welcome addition to the portfolio. As a new area, it also lacks some level of definition. Such unclear definition is not unexpected, and it was our intent to point out these issues when apparent in the project reviews. The Review Panel's aim is to help the BETO program and technology managers to improve the scope and definition for the WTE Technology Area. We advocate for WTE to remain part of the BETO portfolio with an expanded array of projects. The Review Panel, while mostly consistent in assessing the relative merits of individual projects presented, has also sometimes provided very different evaluations of individual projects. When relevant to an overall assessment of the programmatic area, specific aspects of individual projects may be discussed.

As a general observation, the need to maintain each presentation within reasonable time limits may sometimes make it difficult to convey results, methods, and project context adequately. The PIs' responses to the reviewers' comments make it clear that some of the gaps we have identified were known to PIs. The reviewers' perception was amplified by the presentation format and the relatively short time allowed to present complex projects. We feel that there are a few areas where the presentations could have been improved by a template to support a more cohesive assessment, namely the following:

- It would be beneficial to always have a table that, when applicable, shows targets versus achievements to date—to have an immediate assessment of whether the goals were achieved or not and by which margin the goals were missed or surpassed. No explanation is needed, as this can be addressed in another part of the presentation and in the Q&A with the reviewers.
- We would benefit from a clear summary of assumptions with respect to TRL and techno-economic analysis (TEA). During the review, it was often clear that the panel members and the presenters were not aligned on these assumptions. Such an alignment often did not occur during the discussion and emerged more clearly only when PIs responded to the panelists' comments.

Impact

The WTE Area has been established to identify opportunities for "wet" and low-bulk-density streams, which will not be suitable for technology aimed at more conventional biomass sources. These include sludges from wastewater treatment plants (WWTPs), manure, and food waste. The United States has much infrastructure, which can be leveraged for WTE both in the large number (exceeding 15,000) of WWTPs in the United States and an extremely developed agricultural sector with significant concentrated animal feeding operations producing a large amount of manure. Today, only a fraction of that manure is captured for biogas production. In the case of wastewater treatment, a large distributed infrastructure is available. In the context of WTE, we should not ignore municipal solid waste (MSW). MSW is not a "wet" stream in the way the others are, but it is a considerable source of cellulosic material, as recognized in other BETO programmatic areas. Given the interest that MSW is raising as a carbon source for biorefineries and its recent inclusion in the *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy*, we expect that, in the future, MSW will be directly included in the WTE Technology Area—especially unsorted MSW, which is poorly suited as a source of refuse-derived fuel and is sent to a landfill. Key technologies addressed by the WTE Area, such as AD and hydrothermal liquefaction (HTL), can certainly use the organic fraction of MSW as a feedstock. We therefore consider MSW a natural extension of the scope of the Conversion Program Area.

WTE feedstocks have some characteristics in common: they are highly distributed, are ubiquitous, and can provide significant contributions at the local level. They are also unsuitable for transportation, which limits aggregation and, consequently, the scale of projects. Hence, the local and distributed component of any solution is essential. In this area, the Review Panel reached a consensus that projects such as Waste-to-Energy: Feedstock Evaluation and Biofuels Production Potential can be highly impactful, as confirmed by the scores awarded. The value of inventory tools—especially when enhanced by Geographic Information Systems—to the practitioners cannot be underestimated. We strongly feel that this area is one where the national laboratories can provide unparalleled leadership by developing tools and methods accessible to the larger community of researchers, engineers, and project developers. The WTE Simulation Model, while having the potential to achieve a similar impact, was considered lacking adequate granularity for such distributed feedstock infrastructure. We do, however, encourage continuing the effort while refocusing on a more bottom-up approach, as discussed in the specific project reviews. Ultimately, it was the Review Panel's view that system dynamics models can be a valuable support tool for the industry.

While WTE feedstocks exist in already-developed supply chain infrastructures that provide known and predictable economics, these feedstocks are also often highly regulated. The tight regulation and the mission-critical nature of some of these facilities—such as WWTPs—fosters a cautious operating culture that is skeptical of change. These aspects—the highly regulated nature of the industry and the culture that it fosters—need to be considered, as they raise the bar for the adoption of novel technologies, especially when it may impact the facility's core mission. An example of this is seen in the project, Hydrothermal Processing of Biomass. It is our view that the assumption to integrate the HTL recycle water into the front end of the WWTP—discussed in detail in the project review—will require careful assessment, as it may not be compatible with the needs of plant operators. This want in integration analysis, in turn, may limit or delay the positive impact of an otherwise very promising. Lastly, any advancement in AD technology and biogas utilization can spur the further development of biogas resources, which are currently substantially underdeveloped. The strong focus on biogas in a variety of projects is of clear value and impact. Technologies that allow whole-carbon utilization—methane and CO2—of biogas can be particularly impactful here, as highlighted in the Biogas Valorization: Development of a Biogas-to-Muconic Acid Bioprocess project and projects that develop novel tools to improve the operations of digesters (as in Electrochemical Monitoring of Anaerobic Digestion). We commend the intent of Enhanced Anaerobic Digestion, which is in principle very aligned with the goals of this programmatic area. Regrettably, the project falls short of expectations for reasons discussed in the project review. The area addressed remains one of importance, and we hope it may be better addressed in the future.

Innovation

Projects leading to enhanced/improved AD and use of biogas for added-value products show substantive potential benefits. This is also an area where considerable innovation is needed and can be achieved. The projects Biogas to Liquid Fuel and Chemicals Using a Methanotrophic Microorganism, Biogas Valorization: Development of a Biogas-to-Muconic Acid Bioprocess, and Lactic Acid–Producing Methanotrophic Bacteria for Fermentation of Bio-Methane as a Biological Upgrading Technology indicate the opportunities and challenges of using biogas as a feedstock for bioprocessing. While these projects largely focus on metabolic optimization of specific organisms, they have already identified possible innovative solutions in reactor design. Bioreactor design advances are needed to address the unique challenges of biogas fermentation with respect to mass and heat transfer. Addressing these challenges in turn makes it possible to identify the optimal scale at which biogas can be economically used for these processes. We can already infer that these future bioprocessing facilities are necessarily limited in scale, and the transportation of suitable feedstock to larger ad-hoc biogas facilities is most likely economically unfeasible. The Review Panel was intrigued by the concept of a falling film reactor built with low-cost material, which is proposed in one of these projects. If successful, the combination of an optimized microorganism for biogas utilization with low-cost, scalable reactors that achieve high mass and heat transfer without considerable energy inputs would be a game changer for the industry. We feel this is one of the most significant innovations that could emerge from this program. Overall, we feel that whole biogas (both methane and CO_2) and raw biogas (biogas and contaminants other than CO_2) utilization is a critical area of innovation.

While AD is an old technology with plenty of industrial applications, it is still fundamentally rooted in empiricism, and we still have a limited understanding and an even less-effective way to control the behavior of large microbial consortia on highly complex substrates. Control of biogas systems is largely reactive, using biogas production as the main measure of performance. In systems with very slow dynamics—and, in many cases, also clear anisotropicity—the record of dropping gas production is an indication of an already severely compromised system. New monitoring and control techniques that improve AD system control may in turn improve AD economics and flexibility. For this reason, the Review Panel appreciates the Electrochemical Monitoring of Anaerobic Digestion project. Simple, inexpensive monitoring techniques and devices that can provide a more direct indication of the performance of the digester will enable better control and, therefore, utilization of existing AD assets. These techniques also promise to be a key enabler for the development of other digestion processes, which would greatly enrich this programmatic area.

Extracting value higher than the energy value of the stream of lignin derived from biorefinery operations has long been one of the industry's most elusive goals. The approach presented in Biomass Electrochemical Reactor for Upgrading Biorefinery Waste to Industrial Chemicals and Hydrogen shows an example of innovation of which we hope to see more in the future. While, at this time, the scalability of the solution is not yet clear and there are several uncertainties on the eventual commercial feasibility, the approach was mostly promising. In particular, the idea to target existing products and exploit the wet lignin as is, rather than extracting a specific chemical, could be a key enabler for commercialization. The PI on the project should be commended for the project's strong collaboration with the private sector. This project demonstrated the importance of early-stage involvement of commercial stakeholders.

Synergies

Considerable publicly and privately funded R&D efforts exist around methane utilization. Given the cost and availability of natural gas, interest in methane as a carbon source is high. The synergies between methane and biogas utilization are evident, although biogas imposes unique challenges due to methane dilution, contaminants, and limited scale. This synergy has two dimensions. On one side, it should push the R&D focus on WTE towards biogas-specific topics, such as the impact of CO_2 dilution or biogas-specific contaminants. On the other hand, it is important to identify at which volume scale—since biogas is a distributed resource accessible only in relatively little individual pools compared to natural gas—downstream technology may work or not work with biogas. The first topic was addressed in the portfolio. The latter was not. This synergy—and to a certain extent conflict—was most evident in Lactic Acid Producing Methanotrophic Bacteria for Fermentation of Bio-Methane as a Biological Upgrading Technology. This project has preliminarily shown that CO_2 dilution may be a significant inhibitory factor in methane conversion, as the solubility of methane in the liquid phase is further reduced by the presence of CO_2. If total carbon utilization is not possible, we see opportunities to focus on reducing the cost of biogas pretreatment. This reduction would also increase the opportunity for pipeline injection of biogenic methane and, ultimately, further expand the synergy between methane utilization and biogas production. Although this topic was not a particular focus of the WTE Technology Area, we believe it may be an interesting area to explore for future activities. The project Enhanced Anaerobic Digestion addressed higher-quality biogas production and is in line with this intent, but we had no consensus on its merits and the actual state of development. Ultimately, some of the projects addressing biogas conversion may find an easier path to commercialization using natural gas and getting credit for renewable methane injected in the pipeline.

Focus

As an emerging area in the portfolio, there was still a perceived lack of a strong topical focus, and many of the projects could easily have found a home in other programmatic areas within BETO, although none was clearly or obviously misplaced in the WTE Area. Nonetheless, the main thread was wet-low or no-value feedstock use, with a strong sub-theme of biogas and biogas-related technologies. We believe this should remain the primary focus of the area. An emphasis on reducing the capital intensity of AD should also be part of this programmatic area. As mentioned, these topics are in part addressed by Enhanced Anaerobic Digestion. Without entering into details that are more appropriately discussed in the detailed project review, this project also shows some lack of clear focus, as it commingles two research areas with limited interaction. Future larger consideration of the organic/cellulosic component of the MSW could also fit this thrust, especially if addressing the use of unsorted MSW, which would otherwise go into landfills. Lastly, while it was well-received, the single project dealing with the use of wet lignin from a biorefinery was also apparently not as connected to the main theme as all the other projects followed. Nonetheless, as lignin valorization remains a key challenge for the development of biorefineries, we believe that acknowledging wet lignin as a waste may enable new innovative solutions, like the one presented in Biomass Electrochemical Reactor for Upgrading Biorefinery Waste to Industrial Chemicals and Hydrogen.

Commercialization

This report already identifies some critical gaps to overcome before commercialization. As mentioned earlier, system modeling and inventory efforts need to address the local nature of WTE feedstock availability. Lack of granularity may limit the audience for this effort. In the case of WTE system modeling, our recommendation is to take a clear bottom-up approach and focus first on selected regional areas—for instance, a large urban area—and then expand the modeling effort.

The fact that this programmatic area is not directly addressing MSW may or may not be a gap, depending on how the WTE Technology Area is defined. The Review

Panel, while not having a clear consensus on this, leans towards inclusion, and we recommend that a clear determination is made as the WTE Technology Area continues and the portfolio may expand.

We noticed some common gaps, some of which may have impacted the ranking of projects. We understand that a detailed analysis of the regulatory barriers may be too early and unduly cumbersome for most projects at this stage of definitions. However, given the importance of regulatory issues in the WTE Area, we found the complete absence of considering regulatory issues surprising. We believe this is particularly relevant for technologies, such as HTL, aiming to co-locate with existing WWTPs. At a programmatic level, this becomes critical as policymakers may ultimately look at the direction set by these programs to identify policies.

There were larger gaps in the lack of consistent presentation between projects. In particular, we lament the lack of consistency in how TEA data and assumptions were presented. The lack of consistent communication appeared in some projects where it was not immediately clear what the stage-gate goals were and if those goals had been reached or missed. While, in part, this is the artifact of necessarily limited presentation times and of the need to preserve the confidentiality of critical intellectual property (for a project led by the private sector), we do nonetheless feel that this area could be improved.

The lack of consistency in the TEA was also quite evident. Some projects did not address it at all. Once more, we do understand that a very early stage of technology development with too much detail on the TEA can become an undue burden. We believe that TEA can help if used in the context of a scenario analysis, such as "under which conditions will this technology reach my benchmark?" The benchmark itself can be based on future expectations rather than present. For instance, in biogas-related technologies, today's natural gas prices may be an impossible benchmark, but higher prices in the future are plausible. These would be a good reference that is also aligned with the long development and commercialization time of these technologies. Ultimately, we believe that even when a detailed TEA is not in the scope of the project, appropriate TEA elements should be included.

Finally, with some exceptions, we noticed a disconnect with the possible private or—in the case of wastewater treatment—local government stakeholders. When more detailed TEAs were presented, some key financial benchmarks were not in line with industry standards, and the assumptions on end-product value and quality were wanting. Moving forward, TEA assumptions and results will benefit from better vetting and earlier challenge of assumptions. We believe that addressing the lack of consistency in the TEA will also help to address a gap we often noted between the end of the project and the follow-up towards commercialization.

The last apparent gap is the use of HTL as a benchmark for a variety of WTE opportunities and characterizations. While we do not argue against its potential, HTL is not yet a well-known and established technology. Most importantly, it has yet to be implemented on a commercial scale. Because of that, it may not be a meaningful benchmark for the general practitioner in the industry. This critical audience, on the other hand, is very well-versed in AD, and we consider AD a better benchmark. Given its potential, we do not argue for scrapping HTL as a point of reference, but for the foreseeable future, we advocate also using AD as HTL establishes itself as a viable commercial solution.

The analysis of these commercialization gaps should not detract from the programmatic value of the WTE portfolio. This value will be enhanced by addressing the gaps, none of which significantly impact the high scientific value and rigor of the projects presented.

Recommendations

The recommendations for the further development of this programmatic area reiterate suggestions in part already expressed elsewhere:

- Continue and extend the focus on the fundamentals of AD, from microbiology to enhanced control and monitoring.
- Develop methods and standards that the industry may be able to adopt. Use realistic benchmarks that relate to the industry and can be used by practitioners in the area.
- Continue the modeling and inventory efforts, but recalibrate the modeling effort starting at the local level rather than at the national level. Those are of immense value to the industry, and no place is better suited than the national laboratories to lead this work.
- Include a more direct consideration of existing regulatory and operational constraints in the evaluation of projects/technologies and their route to adoption. While no project should be rejected purely based on regulatory constraints, it should be clear that the higher the regulatory hurdle, the higher the benefits need to be to justify regulatory changes and the longer the adoption time. These issues should also be reflected in the TEA.
- Projects that do not work well with biogas—because of scale or other considerations—may work well with methane, and we believe there should be a stronger focus on biogas upgrading technology. However, projects that may not function well with raw or only partially conditioned biogas with sufficient scale of biogas availability at a single source do not belong in the WTE Technology Area. This observation is not to discourage BETO to initiate these projects, but to define clear benchmarks for understanding when further work on the technology may be better carried out in another programmatic area, regardless of the project's technical merits.
- Lastly, while this is not directly related to the programmatic area (but is consistent with the observations present elsewhere in the report), improve the presentation format during the Peer Review.

WTE PROGRAMMATIC RESPONSE

Introduction/Overview

BETO thanks the Review Panel and the PIs for their time and efforts to improve our portfolio. BETO appreciates the reviewers' concerns about presentation format and consistency and will work to improve these areas at future reviews.

Because WTE is a relatively new area in the BETO portfolio, we realize that many areas are still emerging, and in some cases scope may not have been clear to the Review Panel. One such area was the role of MSW within the WTE portfolio, which will be clarified going forward to avoid confusion. While the focus of the WTE resource assessment has primarily been on high-moisture feedstocks (e.g., sludge and manure), cost-benefit analyses and infrastructure assessments will be conducted in Fiscal Year (FY) 2018 to consider all organics included in MSW. BETO was also encouraged to hear the appreciation for WTE as a solution to waste lignin. Lignin utilization continues to be an increasingly important topic of BETO's portfolio in FY 2018, addressed primarily in the Biochemical Conversion portion of the Conversion R&D Program.

We agree that biogas from WTE has synergies with methane from other non-biomass sources. To this end, BETO is engaged with DOE's Office of Fossil Energy to seek synergistic activities in this area. BETO focuses specifically on innovative technologies that may upgrade biogas or biogas precursors to liquid transportations fuels and bioproducts, utilizing technologies that are efficient at the scale of WTE feedstocks.

We agree that when pursuing innovation in WTE conversion, concomitant analysis in mobilizing distributed waste feedstocks is critical. This analysis may include understanding logistics/handling and evaluating scalable, localized technologies. The comments from the Review Panel are noted. Additionally, we note the Review Panel's comments on more consistent TEA.

The following sections address the three top recommendations from the Review Panel:

Recommendation 1: Extend the Focus on the Fundamentals of AD

We agree with the Review Panel that we should extend the focus on the fundamentals of AD (microbiology to enhanced control and monitoring). BETO has specifically identified a systems biology understanding of AD as an area of interest in the FY 2018 WTE laboratory call. Interests include an improved understanding of bacterial and archaeal community dynamics within digesters, as well as toolkit development, including omics.

Recommendation 2: Develop Methods and Standards for Industry

We agree with the Review Panel on the importance of developing methods and standards for industry and of using realistic conversion benchmarks (as opposed to just HTL). Future analysis efforts, including those in FY 2018, will include more industrially accepted baselines for evaluating resource potential, e.g., AD as a baseline conversion for sludge and manure, and compost for food waste.

Recommendation 3: Recalibrate Modeling Efforts to the Local Level rather than the National Level

We agree to recalibrate the modeling effort starting at the local level rather than at the national level. BETO hosted a workshop in California in June 2017 to learn more about WTE resources and policy frameworks at the state level, including policies surrounding emissions reductions and carbon intensity of fuel use, regulations surrounding pipeline injection, and site permitting. While BETO does not make policy, it can inform policymakers and pursue new technologies that address the constraints that industry has in meeting current policy and regulations.

To follow up, we are working with the Waste-to-Energy: Feedstock Evaluation and Biofuels Production Potential project on ramping up resource assessment activities to establish regional and state supply curves that utilize county-level (and point-source) resource data available for sludge, manure, biogas, food waste, and fats/oils/greases. The WTE Simulation Model project is also exploring WTE modeling on a state and local level. A California-specific model will be developed by the end of FY 2017. Future efforts will look at other regions and leverage synergies where possible, while also addressing unique localized challenges and opportunities. Improving these models will enable BETO's WTE Technology Area to serve as a streamlining tool to enable synergy across different regions and states of the United States, while respecting the specific key challenges and opportunities any one state must address.

WTE SIMULATION MODEL

(WBS #: 2.1.0.104)

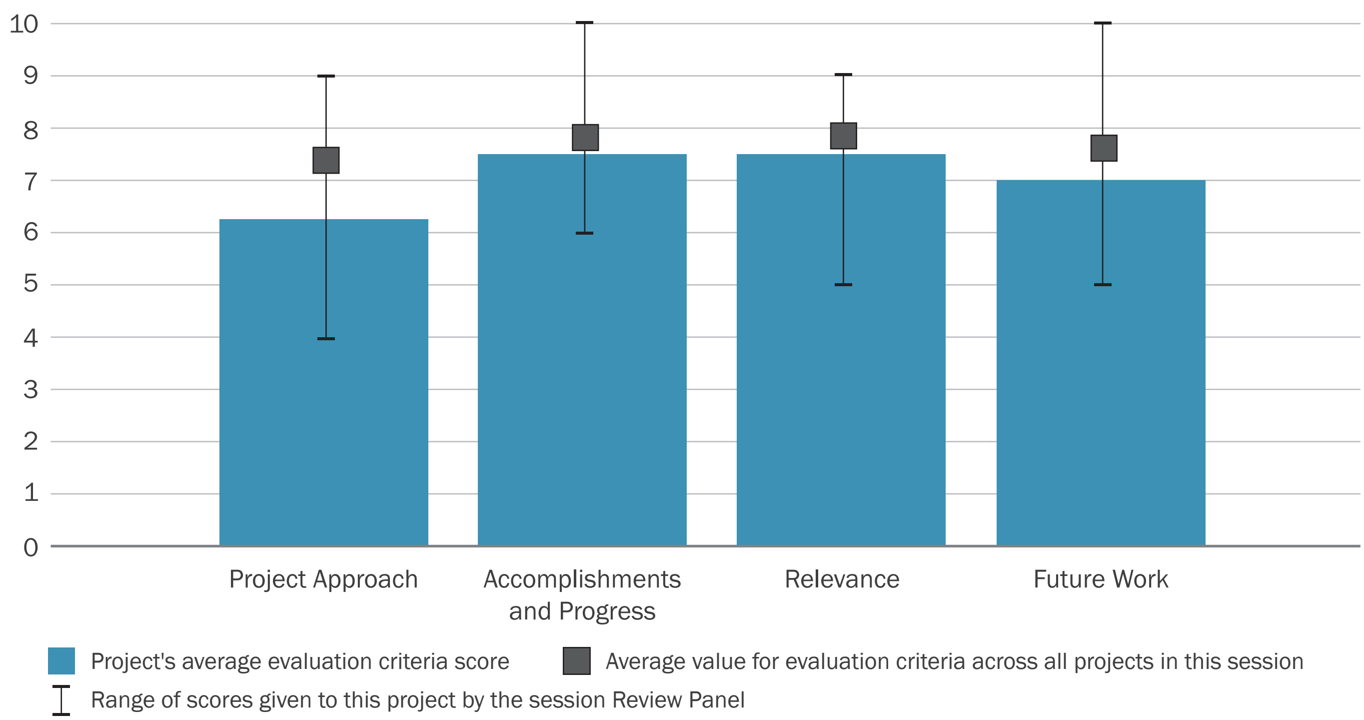
Recipient:	National Renewable Energy Laboratory
Principal Investigator:	Danny Inman
Project Dates:	5/1/2015–9/30/2018
Project Category:	Ongoing
Project Type:	Annual Operating Plan
DOE Funding FY 2014:	$0
DOE Funding FY 2015:	$50,000
DOE Funding FY 2016:	$400,000
DOE Funding FY 2017:	$390,000

Project Description

The goal of this project is to build and exercise a system dynamics model of the U.S. WTE industry to gain insights into the industry's development. Project outcomes include a completed and vetted system dynamics model of the WTE system in the United States and analyses that directly address specific BETO questions regarding the development of the WTE industry. This project is relevant because it provides actionable analysis of the nascent WTE industry (e.g., identifying bottlenecks, synergies, impacts of R&D decisions, policy implications, and areas of leverage). The WTE System Simulation Model uses a system dynamics modeling framework. The model is built from vetted and/or published resource, market, and techno-economic data. It uses a flexible, modular, and transparent architecture. Project accomplishments include the following: conducted three interactive model exploration sessions with BETO, completed initial analysis of the energy potential from landfills and concentrated animal feeding operations, updated data sources, and developed a model of the Renewable Identification Number market. Future work will be focused on major model expansion—linking to the Biomass Scenario Model, high-impact analysis of the D3 Renewable Identification Number market, and a large sensitivity study.

Weighted Project Score: 7.1

Weighting: For ongoing projects, there is equal weighting across all four evaluation criteria: Approach, Relevance, Accomplishments and Progress, and Future Work.



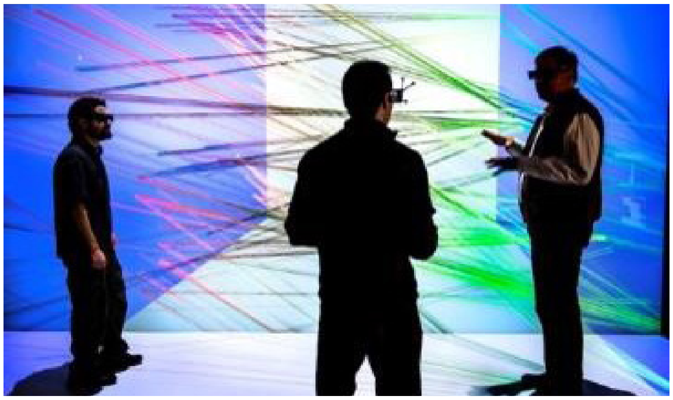


Photo Courtesy of National Renewable Energy Laboratory

Overall Impressions

- This is a valuable modeling exercise with far-reaching benefits to many aspects of the energy sector.

  As with any modeling-driven or based project, one needs to understand how the tool can be used and how it breaks.

- An adaptable, regionalized system dynamics model of WTE systems would be a valuable tool to identify and prioritize investment opportunities.

- The main comment was laid out immediately. We believe this effort, while based on a sound scientific approach and certainly addressing a need of the industry, is fundamentally undermined by the lack of granularity. The integration with the Bioenergy Knowledge Discovery Framework is positive, but ultimately, the lack of granularity makes it of limited use to some of the stakeholders on which the developers may most depend to collect industry data. Those are the practitioners in the field whose work is intrinsically regional. We see utility for policymakers at the national level. Alas, since implementation is often local, the model as it is today may provide scant support to regional decision makers. Overall, the aim of the project is good, but the scope needs refining.

- This project, which is focused on development and utilization of a system dynamics model for the WTE industry, provides an important and useful tool for BETO to explore how the industry may respond to various forces, such as feedstock availability, market behavior, and policy effects. As it is refined and expanded, it will also be useful for other stakeholders in WTE technology, and it is a unique and valuable contribution. There is concern with how universal the model structure is considering potential different responses to the same stimulus by different regional sections of the United States. A recommendation is to focus and verify the model based on localized regions rather than on a national level.

PI Response to Reviewer Comments

- No official response was provided at the time of report publication.

WASTE-TO-ENERGY: FEEDSTOCK EVALUATION AND BIOFUELS PRODUCTION POTENTIAL

(WBS#: 2.2.1.108)

Recipient:	National Renewable Energy Laboratory
Principal Investigator:	Anelia Milbrandt
Project Dates:	5/1/2015–9/30/2018
Project Category:	Ongoing
Project Type:	Annual Operating Plan
DOE Funding FY 2014:	$0
DOE Funding FY 2015:	$40,000
DOE Funding FY 2016:	$640,499
DOE Funding FY 2017:	$690,000

Project Description

The goal of this project is to provide foundational data, strategic analyses, and resource assessment modeling critical to the economic and environmental viability of the emerging WTE industry. It began in the last quarter of FY 2015 to support BETO's objectives in accelerating development of WTE technologies. These technologies offer alternative and sustainable solutions to waste disposal—a growing concern across the nation as population grows—and could present a niche opportunity for the bioeconomy of the future. Our accomplishments to date include the following: (1) An estimate of the wet WTE resource potential for wastewater sludge, animal manure, food waste, and fats, oils, and greases; and (2) an estimate of the biofuels potential from wet WTE sources via HTL conversion process as a "baseline." Our analysis indicates that wet WTE resources have the potential to produce about 9 billion gasoline gallon equivalent per year, about 6.4% of 2015 U.S. gasoline consumption. About half of this potential is generated from animal manure. If an HTL conversion process is utilized, these resources could yield about 6 billion diesel gallon equivalent per year, about 15% of 2015 U.S. on-highway diesel fuel consumption. This analysis provides the first estimate of wet WTE resource potential below the national level (at point location for most

Weighted Project Score: 8.5

Weighting: For ongoing projects, there is equal weighting across all four evaluation criteria: Approach, Relevance, Accomplishments and Progress, and Future Work.

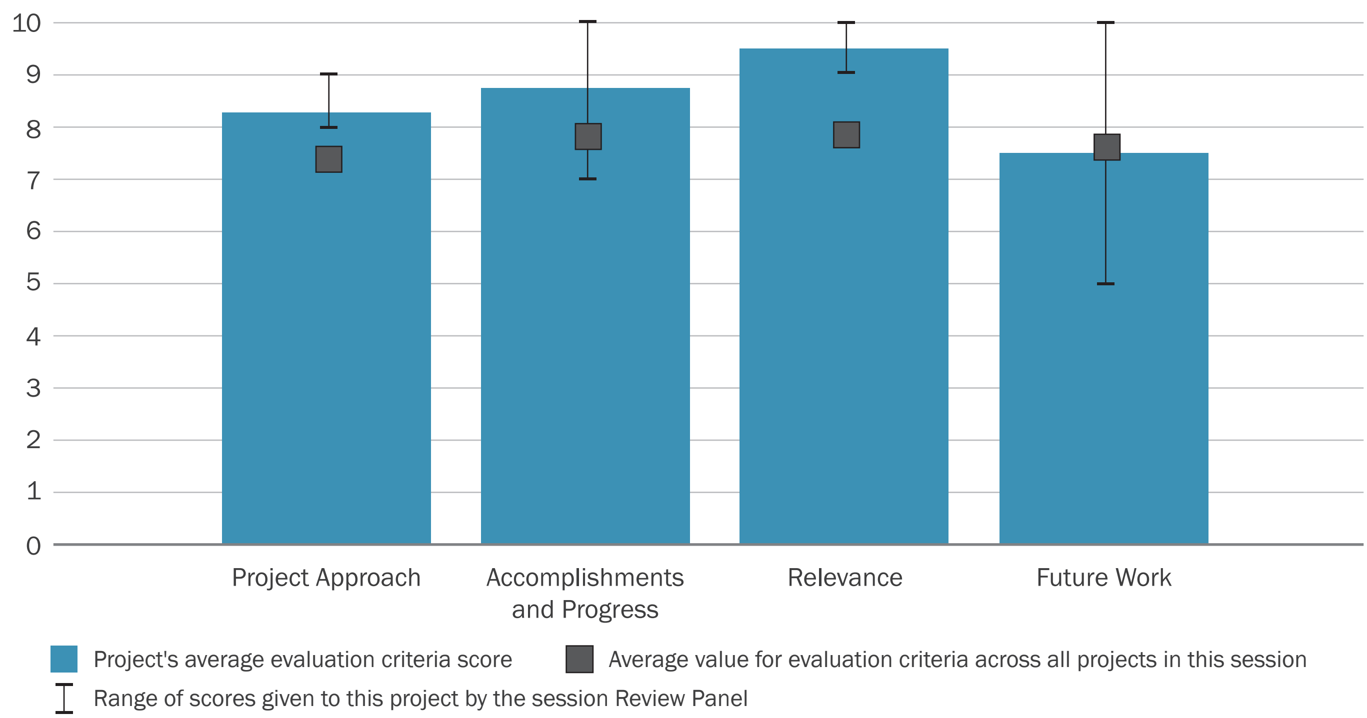


Photo Courtesy of National Renewable Energy Laboratory

resources). Project challenges included data availability and quality, which were mitigated by ongoing industry input.

Overall Impressions

- This needs feedstock costs for TEA relevance (currently unavailable). It would be good to have a clearer methodology for getting that information.

  It is not clear from the presentation deck if the HTL is a good metric for benchmarking; it would be good to clarify, including why it is a good/not perfect choice. It might be more relevant to use wastewater industry metrics as well?
- This project will provide critical data to a growing WTE industry that will facilitate prioritization of strategic investments for market development and technological innovation.
- One question for the researcher is whether the inclusion of poultry manure (litter) should be considered. While, in volume, it is relatively small compared to other animal wastes, it has a very large environmental impact, as seen in well-publicized cases of ground and surface water pollution. Lastly, from a methodology prospective, I believe that the environmental value (or environmental service value) of using waste for energy should be considered. Can we improve the disposal or reduce the disposal of organic chemicals in the environment? Can we provide a platform to recycle them? While I realize that a complete analysis of the "environmental service value" of WTE solutions may be beyond this project, I believe that this project in its last phases can lay the groundwork for this as a future follow-up project.
- This project, which is focused on assessing the size and distribution of wet waste resources and potential energy value of these resources, constitutes a tremendous effort and is of very significant value to the WTE and biofuels/bioproducts industry. The authors are almost too modest in conveying the difficulty and amount of work that has gone in to this effort and the results achieved. The project is clearly of relevance to BETO and is critical to the focus of utilizing the previously underappreciated potential of wet waste materials as a feedstock for useful fuels and products.

PI Response to Reviewer Comments

- We thank the reviewers for their valuable input and support.

  We agree with the reviewers that feedstock cost is very important for TEA. The results of our feedstock cost analysis will be provided not only to the TEA team at Pacific Northwest National Laboratory, but also to the WTE system dynamics modeling team at the National Renewable Energy Laboratory and any other entity requiring that information. Given the time constraints during the Peer Review, we were unable to discuss the details of this task, which is ongoing. We are working closely with industry to gather cost information and will seek industry's feedback on final results.

  There are several reasons we selected HTL as our baseline conversion pathway, as follows:

  - Experimental results to date strongly support HTL as a robust conversion technology potentially well-suited for the wet wastes addressed in this study. This was reinforced by Pacific Northwest National Laboratory's experience with sludge feedstock, as well as specific examples found in the literature reporting successful HTL conversion of each of our target feedstocks to biocrude, a reasonable intermediate for upgrading to transportation fuels.

- This body of experimental results enabled the development and use of a correlation-based HTL conversion model to reasonably and consistently estimate the biocrude production potential for each of our feedstocks. It should also serve as a reasonable model for evaluating feedstock blends.
- Given BETO's ongoing investment in development of HTL, we are now positioned to use the results of this study to help guide the HTL experimental design toward focusing on the most promising feedstocks in terms of their availability and biochemical characteristics.
- Finally, though we used HTL for our initial baseline, we plan to directly compare HTL with AD as part of our future work.

We agree with the reviewer that poultry manure is an important environmental concern. However, it is generally a dry feedstock. The exception is manure from laying-hen operations, which contains more liquid than broiler waste and could be considered as a wet feedstock in the future.

We certainly agree with the reviewers that the environmental value of using waste for energy should be considered. Our plan is to address the environmental value of WTE technologies in FY 2018.

HYDROTHERMAL PROCESSING OF BIOMASS

(WBS#: 2.2.2.301)

Recipient:	Pacific Northwest National Laboratory
Principal Investigator:	Rich Hallen
Project Dates:	10/1/2015–9/30/2018
Project Category:	Ongoing
Project Type:	Annual Operating Plan
DOE Funding FY 2014:	$450,001
DOE Funding FY 2015:	$1,350,000
DOE Funding FY 2016:	$2,200,000
DOE Funding FY 2017:	$2,050,000

Project Description

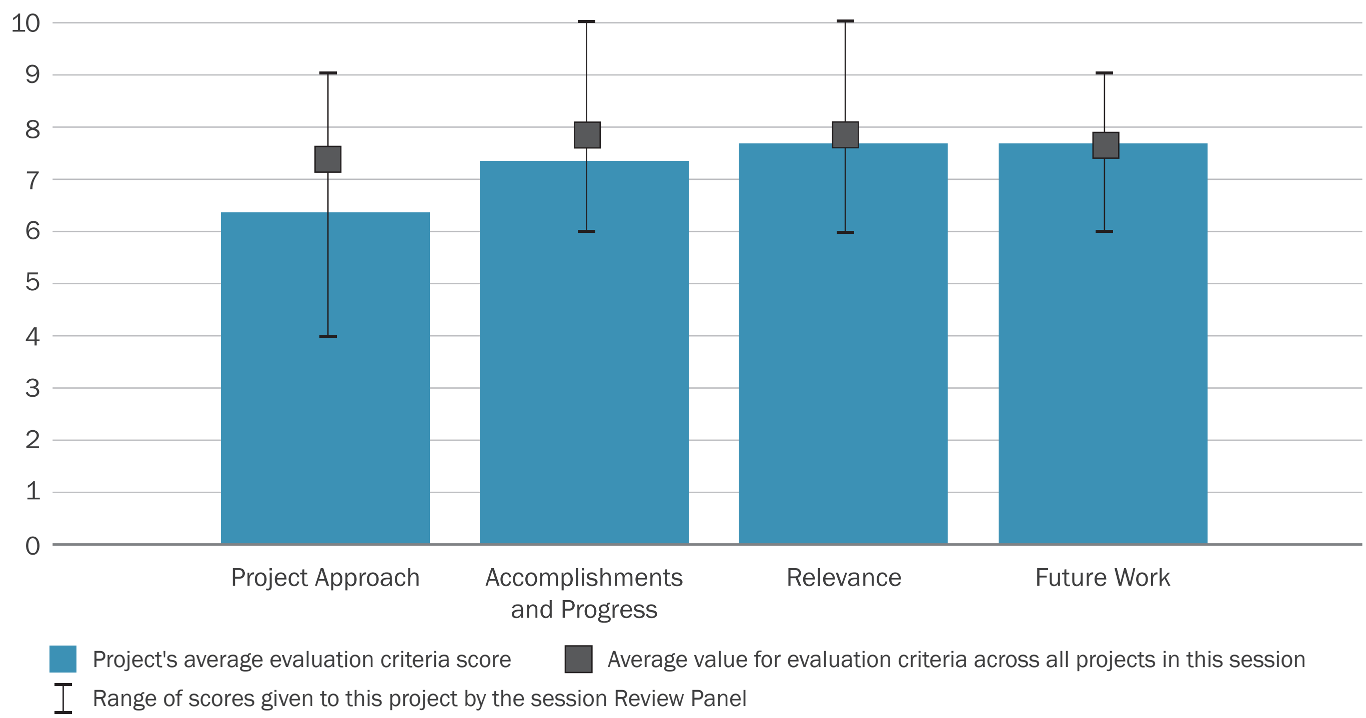
TThis project is working to advance the state of HTL technology, improve overall process performance and economics, and determine the value and best pathway to market for the HTL output products. The HTL technology at PNNL has unique and compelling attributes for producing biocrude from woody, agricultural, and waste feedstocks. This effort will advance the technical readiness/modality of HTL through leveraging existing capabilities, programs, key relationships, and the recent HTL developments under national consortiums (National Advanced Biofuels Consortium and National Alliance for Advanced Biofuels and Bioproducts) and Work for Other agreements. We will focus our R&D efforts on the highest-priority challenges identified in internal and independent TEAs and design evaluations.

Overall Impressions

- This is a very interesting advancement in the technology with promising results. The project is adequately progressing with a clear path for commercialization in many areas. I would like to understand what a broader rollout of the HTL (past the optimal seven sites) will require for commercial viability on yield/efficacy from other feedstocks, from a performance perspective, and/or with capital expenditure in the project goals. What would the yield

Weighted Project Score: 7.3

Weighting: For ongoing projects, there is equal weighting across all four evaluation criteria: Approach, Relevance, Accomplishments and Progress, and Future Work.



improvements and cost reductions that the project team identified that are not included in current TEA estimate do to the rollout potential?

The Review Panel stated that investors will require a minimum 15% return on investment. BETO could suggest the standard financial assumptions to be used by all projects in given areas to keep them on the same scale.

The suggestion was made by the Review Panel to clarify the blendstock work package for the future work.

- HTL has tremendous potential to valorize waste biomass.
- Overall, I find this project has considerable merit and is of great relevance. Unfortunately, I think various methodological approaches detract from it. Nonetheless, the scale at which this was done is considerable and of value. The piloting effort is a considerable accomplishment. The authors need to focus on the next part of the project in strengthening the economic case and studying in detail techno-economic challenges associated with scaling and transitioning this technology. The work to date has demonstrated more than adequate technical viability. The case for economic viability at scale is not clear yet. I hope this can be addressed in the remainder of the project.

PI Response to Reviewer Comments

- We are grateful to the Review Panel for their insights and highlighting techno-economic considerations for commercial application of the process. Many of the questions raised by the panel are of active interest to this project. We are currently addressing process economics from resource availability to the market value of finished products in the design case due to be completed this year. A preliminary TEA/life-cycle analysis has been published. With respect to process scalability, we have obtained a third-party evaluation of the HTL process in previous years by the Harris Group. We have used this evaluation to guide our bench-scale process development and the design of the engineering scale system (modular hydrothermal liquefaction system). We plan to use data from the modular hydrothermal liquefaction system to assess scalability and provide a rigorous basis for pilot-scale system design.

  The comments on refinery integration confirm our current approach with upgrading and characterization of products, but also suggest exploring additional integration strategies with refining partners. During HTL process development within several national consortia (National Advanced Biofuels Consortium, National Alliance for Advanced Biofuels and Bioproducts), Pacific Northwest National Laboratory interacted with refining companies, leading to the current strategy of producing a fuel blendstock for integration. The HTL team recently met with operators of a small refinery to discuss integrating sludge-derived HTL biocrude and received feedback similar to that expressed by the Review Panel. Continuing engagement of the downstream stakeholders will be critical to commercial success. We strive to be grounded, practical, collaborative, and conservative in our approach so that we are testing available and sufficiently abundant resources and producing products that have market, as opposed to theoretical, value. The Peer Review Panel has helped focus our efforts toward that goal.

ENHANCED ANAEROBIC DIGESTION

(WBS#: 2.2.4.100)

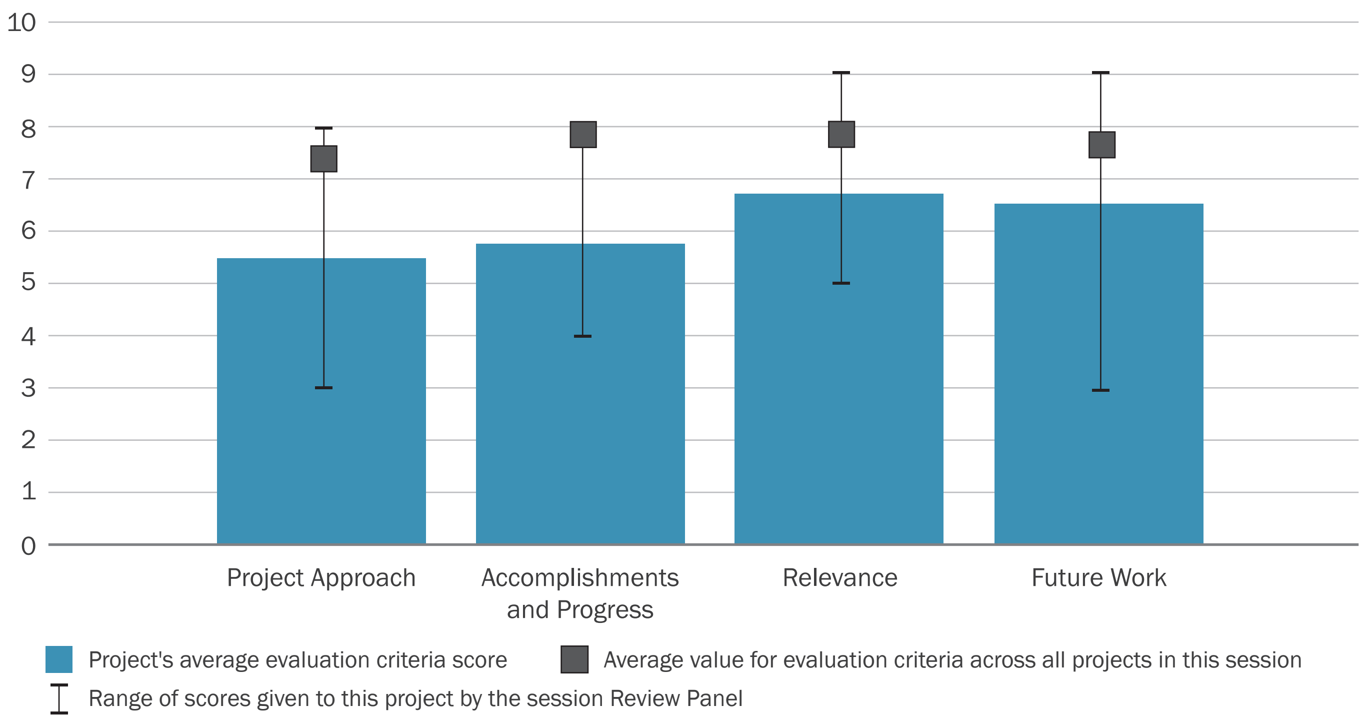
Recipient:	Argonne National Laboratory
Principal Investigator:	Meltem Urgun-Demirtas
Project Dates:	10/1/2013–9/30/2017
Project Category:	Ongoing
Project Type:	Annual Operating Plan
DOE Funding FY 2014:	$500,000
DOE Funding FY 2015:	$750,000
DOE Funding FY 2016:	$750,000
DOE Funding FY 2017:	$550,000

Project Description

Argonne has been developing a low-cost WTE process to produce renewable methane. The project goals are to transform negative-value or low-value waste streams into high-energy-density, fungible renewable methane through targeted research, development, and demonstration. Our ultimate goal is to reduce biogas production and upgrading costs by increasing biogas quality, decreasing the need for gas cleanup, and increasing the reaction rate and yield. We started with sludge generated during wastewater treatment as carbon and energy sources and produced a biogas with ~90% methane content—rather than 55%–70% methane (volume/volume) produced in conventional digesters—using Argonne's novel, low-cost treatment additive process at bench-scale digesters (0.5 liters). We evaluated pathways to piloting and scale-up of the AD process to 14-liter digesters in FY 2016 based on performance results obtained in FY 2015. We considered a variety of factors, including organic and biochar loading rate and retention time that affects the rate of digestion and biogas production in the full-scale digesters, to enhance the gas production and maximize methane content in the biogas (>90% methane). The chemical composition of digestate, left over after AD of waste, was analyzed to determine the

Weighted Project Score: 6.1

Weighting: For ongoing projects, there is equal weighting across all four evaluation criteria: Approach, Relevance, Accomplishments and Progress, and Future Work.



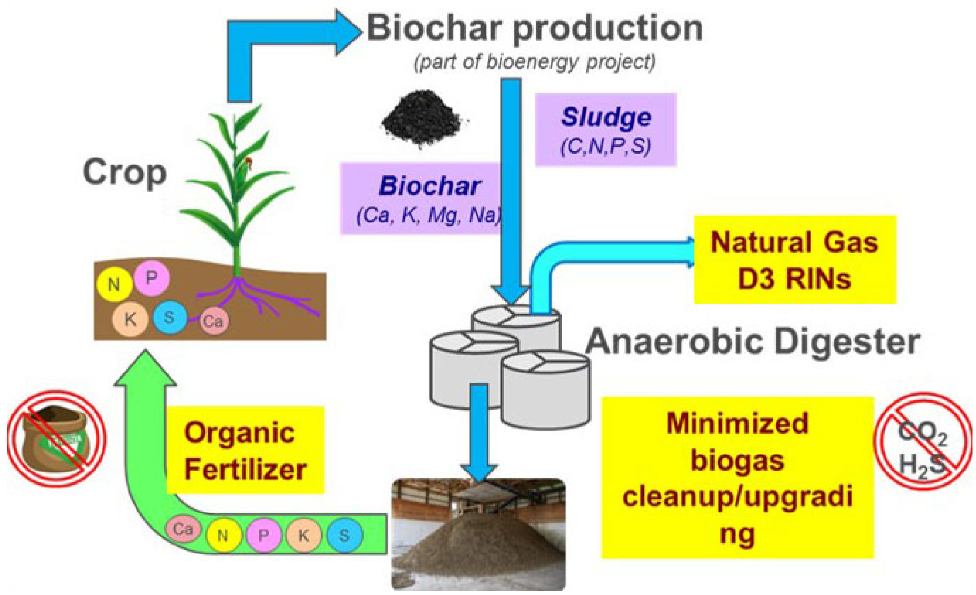


Photo Courtesy of Argonne National Laboratory

fertilizer value provided by biochar addition that can be used for growth of energy crops. We will conduct field demonstration of the additive technology in a full-scale digester in FY 2017.

Overall Impressions

- It would be nice to see the results presented in context of the necessary performance/TEA goals so that it is easier to understand the project's progress towards commercial relevance. What are the implications of the no-go on the hydrocarbon production piece?

  The project has worked on city sludge, but it was stated greater technology relevance is for farmers, where higher total solids up to 10% is relevant.

- Increasing the methane content of AD could increase the value of biogas.

- Overall, the topic and aims of this project are relevant. While there is a questionable link between the two tasks—besides the feedstock—and little technical overlap, each topic has merit. The decision of interrupting one of the tasks, as the results did not support its continuation, was correct and demonstrated an appropriate approach to the evaluation of a project outcome.

- Unfortunately, serious doubts remain pertaining to methodology. The presentation was somewhat confusing, and the data were not completely clear. Most importantly, the scale at which this project was carried out is still bench and not pilot as claimed.

  Lastly, the TEA is wanting, and the assumptions about economics, availability, and suitability of biochar use at industrial scale are weak.

- Both tasks in this project, generation of higher methane content and purity in biogas and liquid fuels from sludge via biochemical conversion, are worthy efforts. Achievement of the target goal of greater than 90% methane in biogas with low H2S at bench and pilot scales is significant, though it would be more helpful if the mechanism (involving addition of biochar to the sludge feed) and effects of the many variables explored in this study were better explained. Recognition of the lack of desired results in the liquid fuels production task and subsequent ending of this task represented an honest assessment of results that did not turn out as expected (through no fault of the investigating team) and was a commendable savings of resources.

PI Response to Reviewer Comments

- The sludge stream has limited carbon and pretreatment constraints and an additional waste stream didn't increase the C/N ratio to 100, which is an optimum condition for producing lipids. It also should be mentioned that a consortium of oleaginous microorganisms also requires the addition of glucose and yeast. The addition of these carbon sources is outside of BETO's goal to develop cost-effective new technologies from lignocellulosic feedstocks.

  The field-scale testing will help us to understand the impact of solid content on the process performance. It should be noted that solid content in the big farm effluents drops to 2%–5% due to washing and cleaning activities in the farms, which generate voluminous amounts of wastewater that need to be treated.

  As indicated in slides 4, 6, 7, and 8 of the presentation and PI talk, the two tasks were distinct but parallel, and they started at different times. BETO combined these tasks for project management convenience since the same feedstocks and AD process were used for both tasks.

  There is no definition for the size of bench-, pilot-, and field-scale applications in the literature since this definition depends on tested technology and reproducibility, scalability, and transferability of the bench-scale results. AD technology is very well-known and can be easily scaled up. We used 14-liter digesters since we can only accommodate 2 weeks of sludge supply because of transportation, storage, and disposal issues during the 1-year continuous digester operations. Sludge testing is considered to be Biosafety Level 2 per the Occupational Safety and Health Administration; therefore, we had to follow stringent laboratory protocols and guidelines.

  Biochar production is an emerging industry in the United States, and therefore, all TEAs will have shortcomings. We used biochar, which is a byproduct of pyrolysis of lignocellulosic materials, to help BETO to develop a biorefinery concept where the byproducts can be used in the subsequent process(es) to develop sustainable and cost-effective technologies. Nevertheless, we are also looking for other alternatives that can replace the biochar, such as bottom ash generated from coal-fired power plants and ash generated from biopower plants.

  The CO_2 removal mechanism is based on natural weathering process and adsorption. These were mentioned in slides 4 and 5 and during the PI presentation. The application number of the patent pending process was also cited for more information. The presentation also included the tested conditions, such as operating temperature (mesophilic versus thermophilic), organic loading rate, and biochar loading rate, as well as biochar type and impact.

LACTIC ACID–PRODUCING METHANOTROPHIC BACTERIA FOR FERMENTATION OF BIO-METHANE AS A BIOLOGICAL UPGRADING TECHNOLOGY

(WBS#: 2.3.1.203)

Recipient:	NatureWorks LLC
Principal Investigator:	Ken Williams
Project Dates:	2/1/2015–1/31/2018
Project Category:	Ongoing
Project Type:	FY 2014—Biological and Chemical Upgrading: DE-FOA-0001085
Total DOE Funding:	$2,500,000

Project Description

In 2013, NatureWorks kicked off joint development with Calysta for biocatalyst/fermentative conversion of methane to lactic acid. In May 2015, NatureWorks began working with DOE-BETO under EE-0006876 to synergize this effort with biogas in support of a business case for cost-competitive biofuels. The project focuses on activities within TRL 3–4, with a techno-economic model at commercial scale defining the sensitivity of lactic acid cost of goods produced for target less than $0.30/pound of lactic acid.

This project supports BETO's mission to achieve less than $3/gasoline gallon equivalent biofuel by creating commercially relevant co-products from waste streams at integrated biorefineries. This project leverages NatureWorks' biopolymer production and markets for lactic acid as a platform chemical. Challenges include the following: (1) low methane solubility in aqueous fermentation media, (2) the need to co-feed multiple gases at high mass transfer rates/allow efficient removal of CO_2, and (3) heat removal from metabolism of high-energy methane substrate. Accomplishments include the following: chromosomally integrated lactate dehydroge-

Weighted Project Score: 7.3

Weighting: For ongoing projects, there is equal weighting across all four evaluation criteria: Approach, Relevance, Accomplishments and Progress, and Future Work.

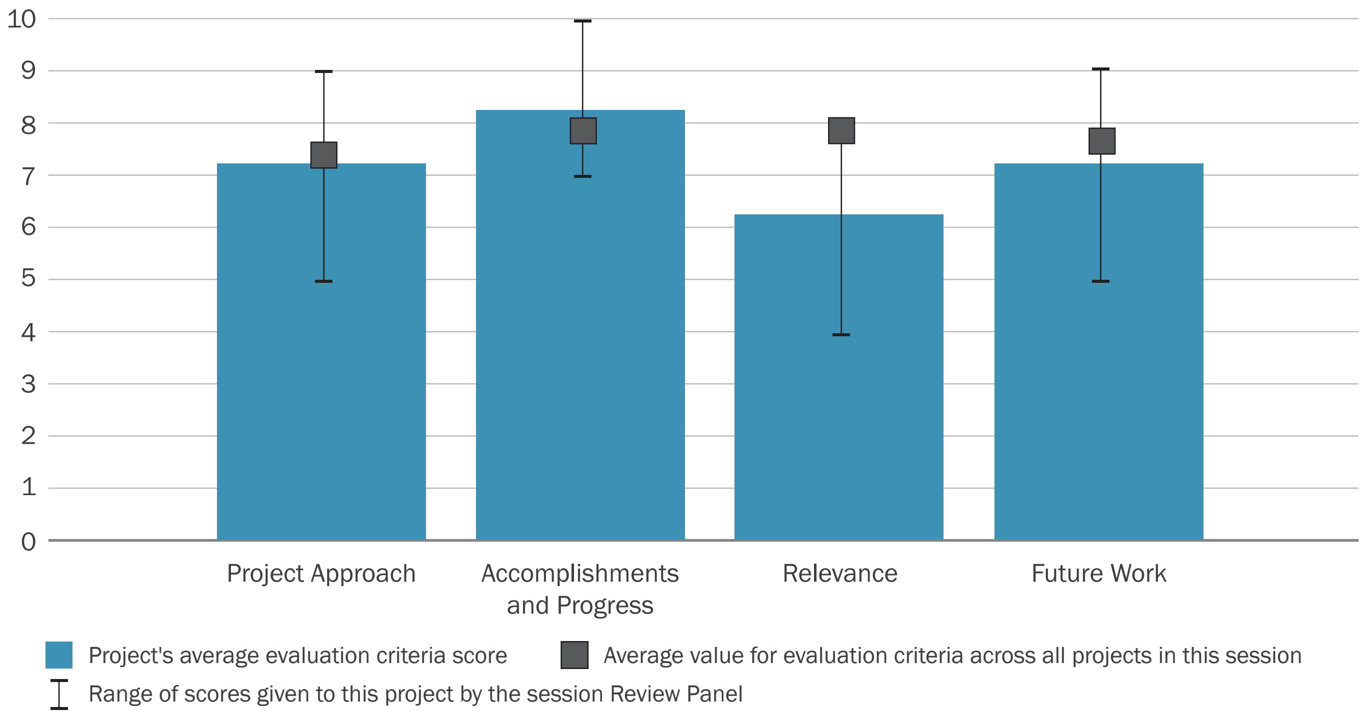



Photo Courtesy of NatureWorks LLC

nase strains; validated promoter system; filed successful patent application on engineered methanotroph strain; achieved a 5 order of magnitude titer improvement in under 3 years at 2-liter scale; built gas-fed fermentation laboratory (approximately $1 million) and world-class fermentation/biology team at NatureWorks towards stage-gate goal of $0.90/pound cost of goods produced target; developed opportunity for waste biogas and supply chain from WWTPs.

Overall Impressions

- The stage-gate milestone to go to pilot scale and the anticipated improvements there are a little unclear, as mass transfer historically becomes more difficult as scale is increased. It would be good to clarify the parameters that are known to give this upside, as it may be a good way to avoid stalling the project.
- I would like to see the next steps on strain development at Calysta, as it looks like it may need new tools or paths to realize success with inhibitor sensitivity (lactate, H_2S, CO_2, et al.).
- A core strength of the project is the potential to valorize biogas through the economical production of industrially relevant chemicals.
- I struggled with this project. I think the effort to use methane as a source of carbon for industrial fermentation and to replace carbohydrates has considerable merits.

  My key struggle is that NatureWorks has used BETO funds to supplement a largely self-funded project with the BETO funds going towards biogas rather than methane. After the review, I believe the biogas effort is questionable for fundamental reasons that transcend the quality of the results. Here I repeat points made before.

- I have two main observations:
  - The PI clearly stated that production of lactic acid and polylactic acid adjacent to a single biogas facility is not realistic given the biogas demand, which, for a commercial unit, would require "the biogas production of the whole state of Minnesota," in his words.
  - Results show that CO_2/CH_4 blends are not as suitable of a feedstock as pure methane. This is most likely because of reduced solubility of CH_4 or possibly other inhibitory effects. This, in addition to the unavoidably poorer operating cost of biogas (where around 40% of the gas volume pumped is not available under each circumstance), makes biogas economically less attractive.

  Given these considerations, it appears clear to me that if NatureWorks wants to use biogas for carbon offset and life-cycle analysis reasons, they are better off buying renewable gas credits from biogas producers who do pipeline injection. Scalability and CO_2 issue would be addressed by this approach, and the technical work should then fully concentrate on high-quality, pipeline-grade methane as the most likely feedstock.

  I also find that the capital expenditure associated with the collection of raw biogas from a municipal WTE plant is not quite entirely justifiable. Biogas is mostly CH_4 and CO_2, with smaller amounts of H_2S and NH_3; "fresh" is also likely to be saturated. Creating "fake" biogas in the laboratory is pretty simple. It is true that there are smaller trace amounts of other compounds, but their presence is often very dependent upon the particular feedstock. If those are of concern, focusing on raw biogas from a single source is probably not helpful to scale the process. Removing those—which is done as a matter of course to make the gas pipeline grade—is more useful.

Ultimately, I can't avoid considering this an interesting technical exercise but of scant impact.

- This project is one of three in this session that focuses on genetic engineering of methanotrophs to produce valuable co-products (lactic acid in this case) from biogas. Lactic acid is a valuable product, and successful production at target cost, if achieved, will be significant and worth the effort. Given conceptual and approach similarities, it would make sense to encourage communication and interaction between the National Renewable Energy Laboratory and NatureWorks to make the best use of resources and avoid duplication of efforts where possible. Given the results of notably higher lactic acid production from pure methane relative to biogas and current prices for natural gas, it is unclear whether NatureWorks (as a for-profit company) will utilize any developments made in this project with a biogas feed.

PI Response to Reviewer Comments

- We sincerely appreciate the time and effort the reviewers spent critically examining projects in DOE-BETO's portfolio. It is difficult to fully address the comments and concerns raised in the space available, but here are a few points:

  The stage-gate milestone to pilot scale is NatureWorks' internal milestone and falls outside the scope of DOE-BETO's project. The stage-gate milestone for the DOE project entails hitting specific targets for titer, productivity, and yield at 2-L fermenter scale. In the presentation, we outlined next steps for the projects focused on improving product tolerance.

  The feasibility of providing adequate biogas supply for commercial plant is largely dependent on chemical oxygen demand of influent feeding wastewater treatment facility and size of facility. For example, technical report NREL/TP-5100-60223[33] describes a lignocellulosic sugar–to–hydrocarbon plant that produces enough biogas to support a ~120 million pounds/year lactic acid plant. The PI's point during the Peer Review presentation specifically detailed how much biogas would be needed for our internal design case (460 million pounds/year of lactic acid). The Blue Lake facility where we sourced biogas is producing 26,000 standard cubic feet/hour or ~0.6 million standard cubic feet/day. A 200 million pounds/year lactic acid plant would need 6 million standard cubic feet/day. However, Blue Lake is only the third largest of seven wastewater plants in the Twin Cities area.[34]

  Essentially, Blue Lake produces one-tenth of the biogas a commercial-scale lactic plant would need annually. NatureWorks is fully aware of current limitations and recognizes the challenges associated with first mover disruptive technology deployment, which are consistent with similar value-chain constraints in launching Ingeo Polylactides over a decade ago and are analogous to challenges facing lignocellulosic biofuels deployment today. We applaud DOE-BETO's leadership in this area and will continue our mission towards feedstock diversifica-

[33] R. Davis, L. Tao, E. C. D. Tan, M. J. Biddy, G.T. Beckham, C. Scarlata, J. Jacobs, et al., *Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons: Dilute-Acid and Enzymatic Deconstruction of Biomass to Sugars and Biological Conversion of Sugars to Hydrocarbons* (Golden, CO: National Renewable Energy Laboratory, October 2013), NREL/TP-5100-60223, https://www.nrel.gov/docs/fy14osti/60223.pdf.

[34] "Blue Lake Wastewater Treatment Plant Facts," Metropolitan Council, September 2012, https://metrocouncil.org/Wastewater-Water/Publications-And-Resources/ES_Bluelake2012_combined-pdf.aspx.

tion: performance materials made by transforming whatever are the right, abundant, local resources. The PI sincerely appreciates DOE-BETO's partnership, leadership, and vision to support this effort.

We appreciate the excellent point around synergy between gas-fed fermentation projects in the portfolio and look forward to potential cooperation with the National Renewable Energy Laboratory to tackle this exciting option. The reviewer will be pleased that discussions have already started on this front as a result of the Peer Review meeting.

We thank all the reviewers for their time, feedback, and suggestions.

BIOMASS ELECTROCHEMICAL REACTOR FOR UPGRADING BIOREFINERY WASTE TO INDUSTRIAL CHEMICALS AND HYDROGEN—BCU ALT

(WBS#: 2.3.1.205)

Recipient:	Ohio University
Principal Investigator:	John Staser
Project Dates:	4/1/2016–3/31/2019
Project Category:	New
Project Type:	FY 2014—Biological and Chemical Upgrading: DE-FOA-0001085
Total DOE Funding:	$1,472,724

Project Description

The purpose of this project is to convert, by electrochemical processes, biorefinery waste lignin to industrial chemicals and hydrogen. We have developed nanostructured, nonprecious metal electrocatalysts that demonstrate high activity toward electrochemical depolymerization of biorefinery lignin to substituted aromatic compounds suitable for use in resins and resin binders. The relevance of this project includes use of actual biorefinery waste supplied from a pilot-scale lignocellulosic biorefinery, a controllable electrochemical process to target specific product classes and functionalities, and co-generation of hydrogen for energy storage, all applied to biorefinery economics. The impacts include additional biorefinery revenue targeted toward reducing the cost of producing next-generation biofuel to make it cost-competitive with petroleum fuels. The challenges include potential low selectivity toward desired products, although we can exert some control over the oxidation mechanism by controlling electrochemical reaction energetics that have demonstrated higher yields of targeted product streams. The project outcomes include a continuous electrochemical process to convert biorefinery lignin to industrial chemicals and full TEAs integrating the electrochemical reactor into the biorefinery concept, including process flow diagrams and a market analysis.

Weighted Project Score: 8.1

Weighting: Approach–25%; Relevance–25%; Future Work–50%.

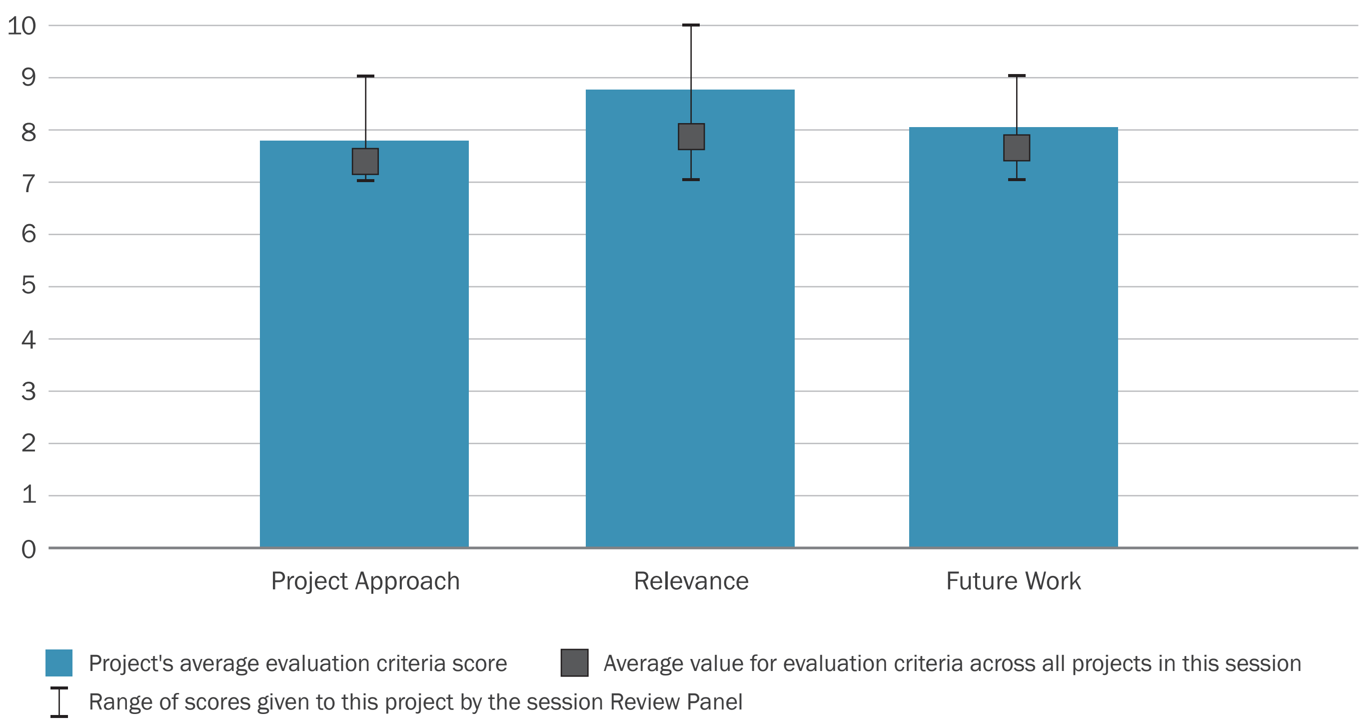


Photo Courtesy of Ohio University

Overall Impressions

- The electrochemical catalyst is a novel approach to the lignin problem. Existing progress gives an early indication of a reasonable chance of success, and an end user is part of the project. There are a few other variables (lignin source, catalyst preparation/carrier, power usage/control) for which it would be good to present an understanding of the degree of variability they will give.

  Testing of different catalysts carriers is a relevant variable for reaching the technical targets; the plan includes some diversity in lignin supply and catalyst production methods to show differences.

- Overall, this project has the potential to develop a new revenue streams for biorefineries through lignin valorization.
- The valorization of lignin beyond heating value is one of the industry "holy grails." The complexity of lignin has been a major obstacle to finding a synthetic route to a higher-value product/utilization. This project has an original technical approach and an interesting commercial goal. The latter targeting the upgrade of lignin as a mixture of molecules rather than focusing on pure chemical makes it possible to greatly simplify post-processing and Q&A. The validation from an industrial partner is of great relevance. The TEA is not as developed as one may want, and I particularly missed an understanding of what the overall market potential is for the proposed enhanced lignin.
- This project, focused on aromatics production from lignin via electrochemical reaction, is unique and innovative. It addresses a waste not commonly looked at to form products not readily available from conventional feedstocks, using a process not often used in biomass conversion technologies, which are typically either biochemically or thermochemically based. The advantages of fine tuning reaction progress through control of the electrochemical potential, as well as operation at ambient conditions, could be a significant advance if it can be proven to perform as presented and if power requirements (especially for a full-scale version) are reasonable.

PI Response to Reviewer Comments

- We currently have one lignin source and are working to procure another. We hope to develop our process on both lignin sources in parallel.

  Electrocatalyst performance and power consumption are both key drivers for this project. We have down-selected electrocatalysts that exhibit high current density (reaction rate) and high selectivity toward target products. We have also targeted running the electrochemical reactor at less than 1.6 volts, which we have achieved in practice. We chose that potential because it is lower than the potential required for water electrolysis, the primary electrochemical technique to generate hydrogen.

  We would like to thank all reviewers for their help, as well as the support of DOE and our program managers. We are excited to work on this project with all of you.

  In general, our primary deliverable is a full TEA incorporating product stream value and energy requirements. We will work with Hexion and the Biorefining Research Institute to complete the TEA by project's end.

BIOGAS TO LIQUID FUELS AND CHEMICALS USING A METHANOTROPHIC MICROORGANISM

(WBS#: 2.3.2.102)

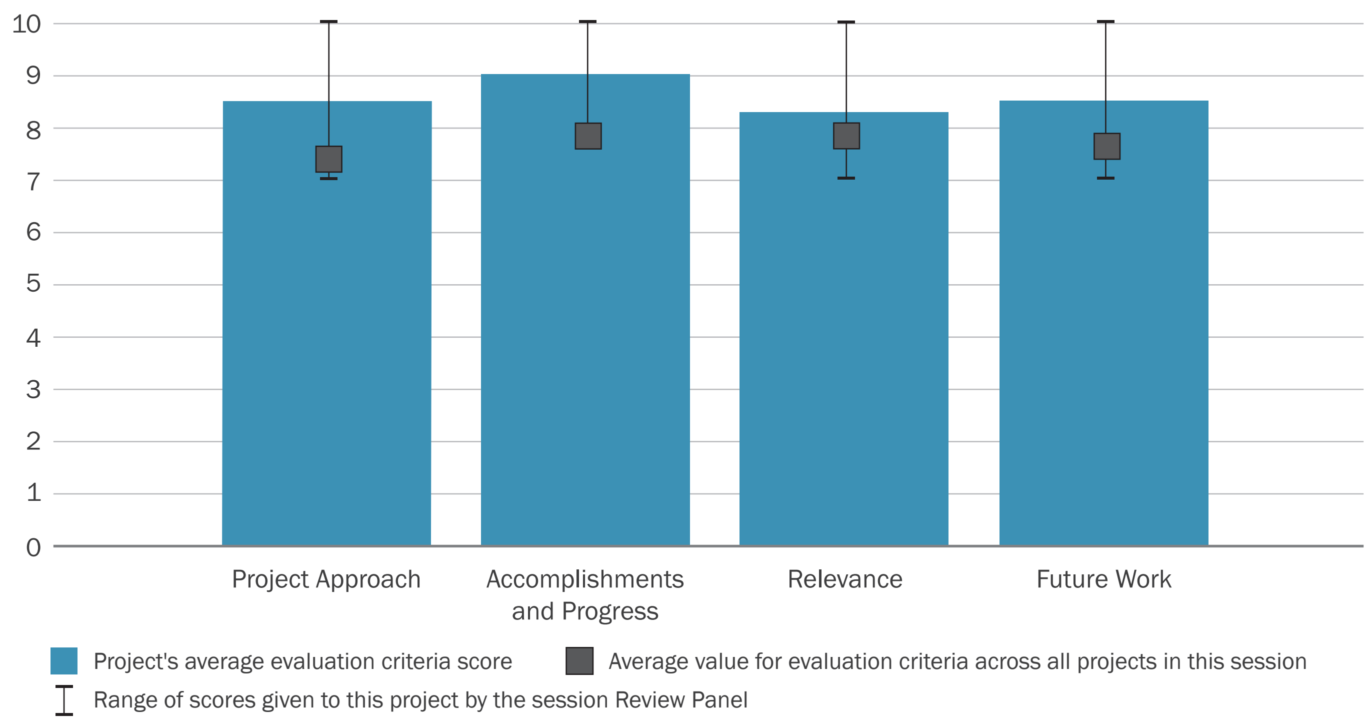
Recipient:	National Renewable Energy Laboratory
Principal Investigator:	Mike Guarnieri
Project Dates:	10/1/2013–9/30/2017
Project Category:	Ongoing
Project Type:	Annual Operating Plan
DOE Funding FY 2014:	$250,000
DOE Funding FY 2015:	$150,000
DOE Funding FY 2016:	$250,000
DOE Funding FY 2017:	$400,000

Project Description

Methane offers a promising, high-volume feedstock for fuel and chemical bioprocesses. Recent advances in gas-recovery technologies have facilitated access to previously inaccessible natural gas reserves, while biogas generated from AD of waste streams offers a versatile, renewable methane source. However, the gaseous state of methane makes for a lack of compatibility with current transportation and industrial manufacturing infrastructure, limiting its utilization as a transportation fuel and intermediate in biochemical processes. Methane bioconversion offers both methane valorization and greenhouse gas emission reduction potential, and it importantly offers a scalable, modular, and selective approach to methane utilization compared to conventional physical and chemical conversion strategies. This project seeks to develop a viable path for conversion of methane to fuels and high-value co-products using a methanotrophic biocatalyst. Initial TEA identified carbon conversion efficiency as the key cost driver is such a process. We have employed genetic engineering and fermentation optimization strategies to directly target yield and methane oxidation rate enhancements to enable economically viable co-production of fuels and chemicals from methane. Our progress has generated the most carbon-efficient methanotrophic biocatalyst reported to date. This work is relevant to the Office

Weighted Project Score: 8.6

Weighting: For ongoing projects, there is equal weighting across all four evaluation criteria: Approach, Relevance, Accomplishments and Progress, and Future Work.



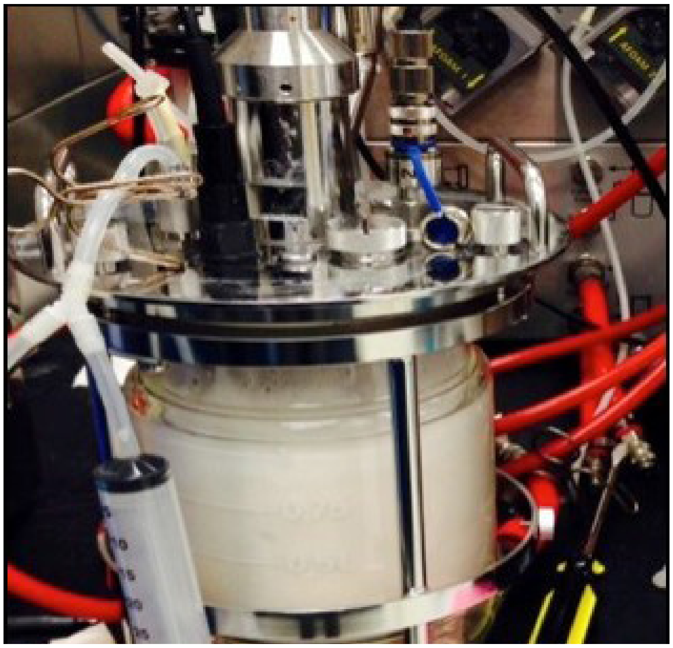


Photo Courtesy of National Renewable Energy Laboratory

of Energy Efficiency and Renewable Energy's *Multi-Year Program Plan* for developing cost-effective, integrated WTE processes and biocatalyst development.

Overall Impressions

- This is an exciting project with great progress already. Toolbox production for methanotrophs is a very important work and very relevant for the application and biotech industry in general. The skilled and experienced project team has been very effective where others have made slow progress using relevant adjacent organism integrations.
- This approach to producing liquid fuels from biogas is sound and has the potential to be impactful.
- This is another project where I struggled. The use of methane as a carbon source is a potentially transformational technology, which cannot be ignored. Overall, the PI did an excellent job in presenting relevant technology of high scientific value and potential high commercial value. The work is of high quality, and the scores are only partially tempered by the considerations that follow, reflect it. I felt that the inclusion of biogas was more to justify the inclusion of this project under the BETO umbrella than a genuine target from inception. A more general issue is whether it makes sense to develop specifically for biogas or if—once the technology for methane conversion has been proven—it is more sensible to incentivize the development of pipeline injection of biogas to make renewable methane available outside the immediate vicinity of an AD system. Pipeline injection is doable today with common off-the-shelf technologies. To use biogas, one needs to address the use of whole biogas (CH_4 and CO_2) and the scale issue. These aspects are recognized but not directly addressed. I recognize that the complexity of the problem justifies dealing first with methane and then with the whole biogas. Success with the first goal and not with the second is still of high overall relevance, although it may be argued that it stresses the envelope on the BETO relevance.
- This project is focused on improving uptake and conversion of methane from biogas via development of methanotrophic biocatalysts. While biogas itself is a useful fuel and, thus, its further conversion is not quite as critical as converting true waste feedstocks (e.g., manure, food waste, sludge), this project has value since liquid fuels are generally more flexible and more widely applicable than gaseous fuels. The project team appears to be well-managed and has produced some impressive genetic engineering results to date.

PI Response to Reviewer Comments

- We thank the reviewers for their positive feedback and constructive project review. As noted by the Review Panel, we feel the development and deployment of genetic tools accomplished under this project scope will have a significant impact upon the burgeoning methane biocatalysis space, as well as a broad impact on the BETO WTE Technology Area. To this end, our metabolic engineering efforts have generated the most carbon-efficient methanotrophic biocatalyst reported to date. The development of such enhanced methane biocatalysis strategies offers a means to expand BETO's feedstock portfolio and represents a significant commercial opportunity to deploy WTE technologies. We also note the potential applicability of the design principles established here to conversion of natural gas, especially associated, remote, and/or stranded reserves. Additionally, we believe this project's efforts offer significant synergistic potential with other conversion platforms, importantly informing gas fermentation design principles and strain-engineering strategies related thereto.

Comprehensive TEAs have identified a viable path to commercialization via conversion of biogas-derived methane alone. However, we recognize the value in complete biogas utilization and have initiated efforts to develop biocatalysts with the capacity to valorize both biogas-derived methane and CO_2. Additionally, future efforts will target development of "downstream" biosynthetic capacity, enabling the generation of broad fuel- and chemical-intermediate suites from biogas. Our team is excited to continue these efforts and looks forward to continued progress in developing a viable biological biogas and natural gas conversion platform.

BIOGAS VALORIZATION: DEVELOPMENT OF A BIOGAS-TO-MUCONIC ACID BIOPROCESS

(WBS#: 2.3.2.201)

Recipient:	National Renewable Energy Laboratory
Principal Investigator:	Mike Guarnieri
Project Dates:	6/1/2015–9/30/2018
Project Category:	Ongoing
Project Type:	FY 2014—Biological and Chemical Upgrading: DE-FOA-0001085
Total DOE Funding:	$2,500,000

Project Description

Biological methane conversion offers a scalable, modular, and selective approach to biogas upgrading. To this end, the Biogas Valorization task targets the development of an integrated bioprocess to produce muconic acid from biogas. The project encompasses the development a novel methanotrophic biocatalyst and a high-efficiency, low-power fermentation configuration. Successful implementation of this target scope will enable facile integration with AD infrastructure and offer substantial biogas valorization potential. Importantly, developments here will also be applicable to an array of substrates, including syngas, natural gas, and CO_2. To date, the project has led to (1) the successful characterization of biogas derived from domestic substrates; (2) generation of novel muconate-producing methanotrophic biocatalysts; (3) development of genome-scale metabolic models for methanotrophic biocatalysts; (4) design and implementation of a high-efficiency, low power falling film reactor; and (5) generation of comprehensive techno-economic models for an array of methane feedstock inputs and organic acid outputs. This work is relevant to the Office of Energy Efficiency and Renewable Energy's *Multi-Year Program Plan* for developing cost-effective, integrated WTE processes to produce bioproducts, and it explicitly targets BETO *Multi-Year Program Plan* barriers, including catalyst development, biochemical conversion process integration, WTE roadmap hurdle, and process intensification.

Weighted Project Score: 8.3

Weighting: For ongoing projects, there is equal weighting across all four evaluation criteria: Approach, Relevance, Accomplishments and Progress, and Future Work.

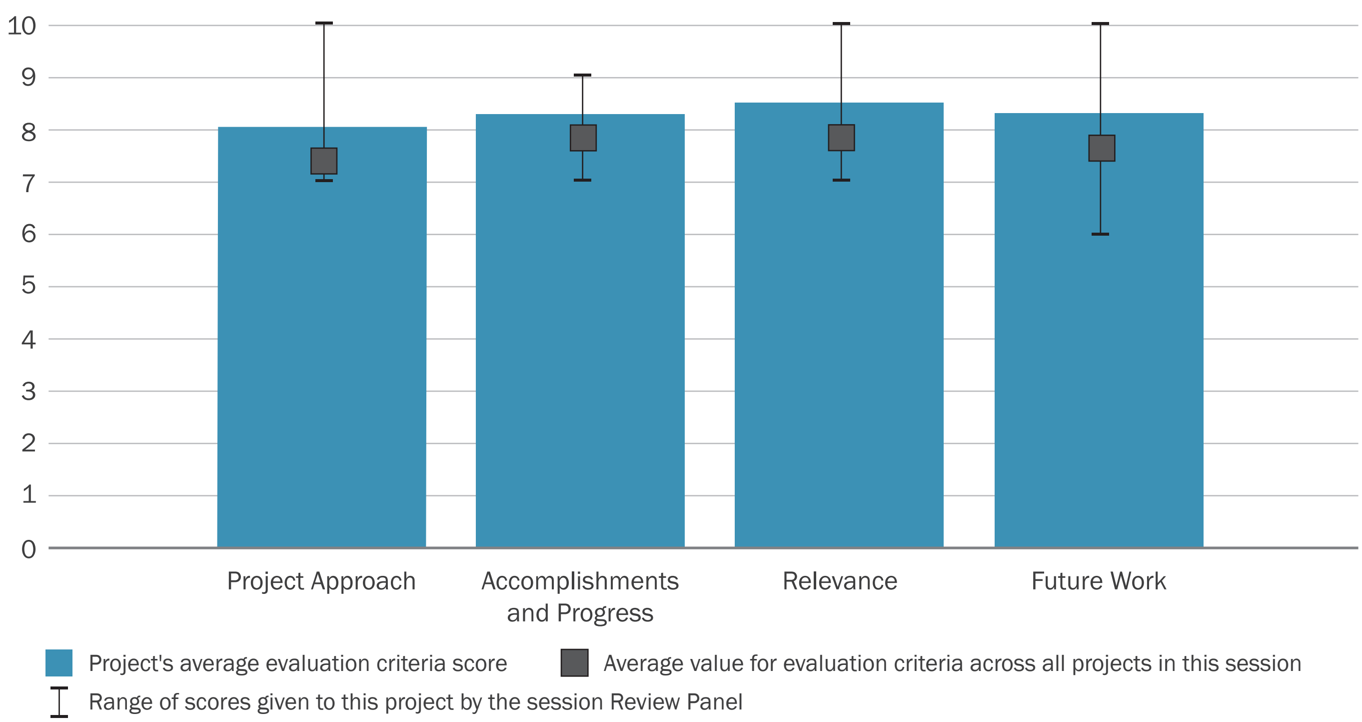


Photo Courtesy of National Renewable Energy Laboratory

Overall Impressions

- This project has a good development pathway and has a lot of tools to achieve the targets. This is a very relevant work with large implications to industry and the Multi-Year Program Plan targets. Use of muconic acid as a target molecule gives it a general applicability to a large market.

  As suggested by a panelist, a key performance indicator for viable cell population during the reactor operations may be relevant. The scalability of the reactor design is also something that will be good to understand in more detail.

  It would be good to establish current position on the TEA goal and update for reporting. It would be good to know the go/no-go with reference to reactor design, as this complex design may be more expensive at scale than expected.

- The potential to increase the value of biogas through muconic acid production (a chemical precursor for many industrial chemicals and materials) is of value and could lead to increased revenue from AD.

- Besides some of the basic considerations regarding the actual relevance of biogas versus just regular natural gas for this type of project, my key comment is that the TEA is still quite wanting. A better analysis could help make better sense of the opportunity afforded by an otherwise highly innovative project.

- This project is another one focused on genetic engineering of methanotrophs for use with biogas feed, although this project includes H2S tolerance, a unique reactor type, and a different end product (muconic acid). The team appears to be well-managed and highly capable on the genetic engineering side, with achievements of significant results. The project incorporates good use and interaction with TEA models. Future integration of the reactor design and biocatalyst in real-time AD will be significant if successful.

PI Response to Reviewer Comments

We thank the reviewers for their complimentary and constructive feedback. As noted by the Review Panel, we are excited about the broad potential impact this work will have on BETO's nascent WTE Technology Area, as well as the larger biogas industry and the bioeconomy as a whole. This project offers a novel route to biogas conversion via an integrated approach, encompassing biogas generation, biocatalyst and bioreactor engineering, in silico analyses, and extensive techno-economic sensitivity analyses.

The proposed reactor design offers numerous advantages compared to conventional gas fermentation configurations, including low cost, modularity, low power input, minimal water (and related sustainability enhancements), and dramatically enhanced volumetric mass transfer metrics. Though beyond the current scope of work, we recognize the critical nature of examining reactor scalability. As detailed to the Review Panel, the potential scalability of the reactor design is grounded is strong design principles related to industrial paper manufacturing and high-speed paper coating technology. Additionally, we are currently considering the impact of the reactor scale via comprehensive, integrated TEAs, which target viable productivity metrics at commercial scale. Following successful proof-of-principle demonstration at laboratory scale, future work will target process scale-up.

We are optimistic that this process configuration offers the potential for deployment in tandem with an array of biocatalysts for production of diverse secreted target product suites from waste-derived biogas. We look forward to evaluation of the proposed integrated bioprocess in our final award year.

ELECTROCHEMICAL MONITORING OF ANAEROBIC DIGESTION

(WBS#: 2.5.2.100-1)

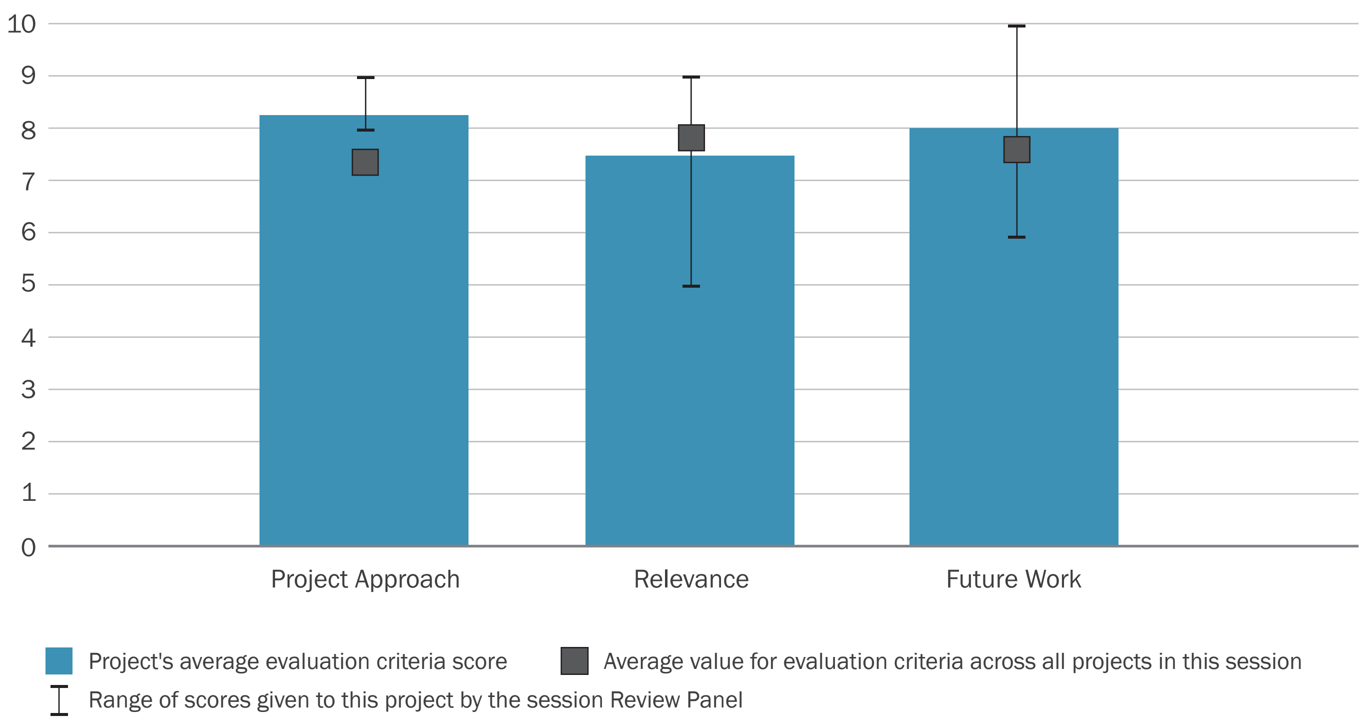
Recipient:	Savannah River National Laboratory, Argonne National Laboratory
Principal Investigator:	Charles Turick
Project Dates:	10/1/2016–9/30/2019
Project Category:	New
Project Type:	Annual Operating Plan
DOE Funding FY 2014:	$0
DOE Funding FY 2015:	$0
DOE Funding FY 2016:	$0
DOE Funding FY 2017:	$159,000

Project Description

The project goal is to develop real-time, in-situ monitoring of microbiological bioprocesses for greater bioprocess control and stability by linking microbial physiology to electrochemical analysis. Specifically, we will address technology gaps that include inadequate process controls that often result in "sick digester syndrome." This will allow us to redefine microbial physiology of bioprocesses in terms of electrochemistry and allow DOE's Office of Energy Efficiency and Renewable Energy and BETO to accelerate near market integration for industrial or institutional applications through reduced stakeholder risk, lower operational cost, improved energy efficiency, and bioprocess control and reliability. We will evaluate mixed cultures for methane production. Savannah River National Laboratory will work in conjunction with Argonne National Laboratory to define microbial activity as an electrochemical phenomenon and define bioprocesses perturbations and imbalanced conditions. This will include incorporation of electrochemical monitoring at larger scale at Argonne National Laboratory to demonstrate that real-time monitoring can be linked to feedback controls. Overall, we will develop and optimize novel electrochemical monitoring technology applicable to many systems, including various methanogenic mixed cultures, for real-time bioprocess

Weighted Project Score: 7.9

Weighting: Approach–25%; Relevance–25%; Future Work–50%.



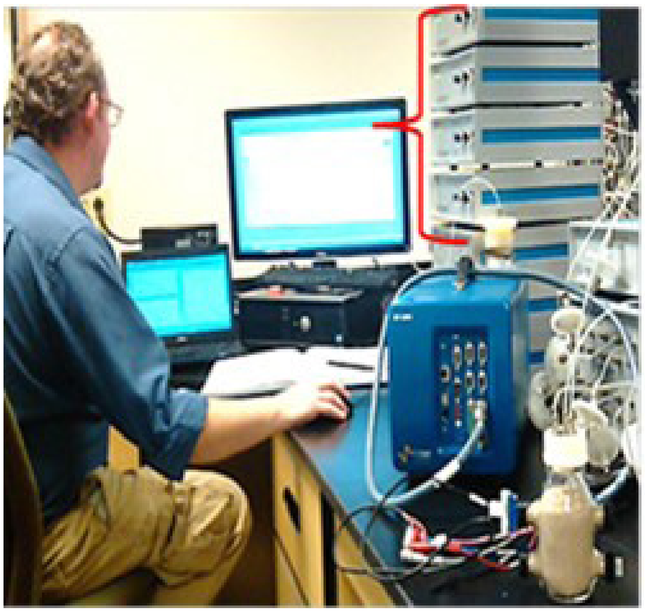


Photo Courtesy of Savannah River National Laboratory

diagnostics, which will identify system upsets sooner than conventional approaches, leading to more stable and efficient operations.

Overall Impressions

- It is not completely clear what the advantage of this approach is compared to near-infrared reflectance, et al., already on the market because fouling made most other easier/cheaper methods ineffective. Perhaps some technology use cost comparison to alternatives, in addition to cost of failure if technology is not used, is needed. A panelist posed a question about how a probe testing just a local area can represent the entire AD; if the cost is significantly lower, maybe you should include multiple probes across the reactors.

  I have some concern with the feedback approach to AD monitoring and control. Most often the issue is a change in feed; should a feed-forward approach also be of value to include in the goals? Several comments were made about what factors to evaluate (tannins, balance, et al.). Can these be defined for relevance with some sort of industry experts and prioritized to include in the project plan?

- This is a novel approach that has significant potential.
- This is a relatively inexpensive project, which, while not devoid of risks, if successful can deliver immediate value to the industry and then enable its further development.

  The successful completion of this project is likely to be only the beginning of a longer process to provide a technology that performs at scale. Some of this follow-up work should be carried out in the context of a possible commercialization as I believe that if the technology can be proven at a reasonable scale, there will be no shortage of opportunity for commercialization. It is important that the PI identifies what that scale is or sets up the program for those follow-ups.

- This project looks to correlate electrochemical and other data gathered through sensors to assess digester performance in real time. If successful, this approach can provide a fast and relatively low-cost method to correct imbalances in reactor biological behavior before the batch becomes unrecoverable, though it is not clear at the present time whether even this data could be gathered fast enough to do so. Nevertheless, the project potential benefits are sufficiently worthwhile to pursue.

PI Response to Reviewer Comments

Existing on-line methods and sensors for CO_2, CH_4, and H_2 analysis, such as near-infrared reflectance, are useful in providing information about current reactor status. However, this is not always straightforward since gas liquid portioning in digesters can be quite dynamic. Additionally, declines in biogas production often represent preexisting problems that may be too late to fix. We feel that one of the significant advantages of our technical approach is the potential for abundant inexpensive data that could incorporate digester sampling as many as four times per hour.

Our approach incorporates evaluation of cellular viability such that issues related to upset conditions will likely be detected in the microbial community prior to metabolite buildup in the reactor. Our future studies plan to incorporate infrared detection for CO_2, H_2, and CH_4 along with electrochemical and digester environment analyses, and we expect the study results to give us information about any potential time lags related to reactor performance and analytical platforms. Our technical approach has the potential for abundant inexpensive data that could incorporate digester sampling as many as four times per hour, if needed.

We will evaluate the application of multiple electrodes as well as electrode design to determine if we can obtain a better representation of bioprocess activity. Multiple electrodes operated simultaneously may be prone to interference through crosstalk. We will keep this in mind as we evaluate designs and configurations. Although one of the reviewers suggested feed-forward analyses, that topic is out of our project scope presently. However, it is an excellent technical challenge that we will consider.

Elevated H_2 and short-chain fatty acids, widely varying feedstocks composition and volume, and elevated organic loading rates are likely the more common inhibitors encountered throughout the industry and are a focus of our study. We will address other inhibitors that may be more specific to particular waste streams (e.g., tannins in agricultural wastes) following interactions with reactor operators that will allow us to categorize them based on relevance. The project team has an established relationship with the AD users and plans to get their guidance and advice during the project. Our ultimate goal is to test performance of new sensors at the field-scale digesters.