WASTE-TO-ENERGY

TECHNOLOGY AREA

CONTENTS

INTRODUCTION

The Waste-to-Energy Technology Area is one of 14 related technology areas that were reviewed during the 2019 Bioenergy Technologies Office (BETO) Project Peer Review, which took place on March 4–7, 2019, at the Hilton Denver City Center in Denver, Colorado. A total of 15 projects were reviewed in the Waste-to-Energy session by four external experts from industry, academia, and other government agencies.

This review addressed a total U.S. Department of Energy (DOE) investment value of approximately $22,750,283, which represents approximately 2.6% of the BETO portfolio reviewed during the 2019 Peer Review. During the project peer review meeting, the principal investigator (PI) for each project was given 30 minutes to deliver a presentation and respond to questions from the review panel.

Projects were evaluated and scored 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. Overview information on the Waste-to-Energy Technology Area, full scoring results and analysis, the Review Panel Summary Report, and the Technology Area Programmatic Response are also included in this section.

BETO designated Dr. David Babson as the Waste-to-Energy Technology Area Review Lead, with contractor support from Dr. Mark Philbrick (Allegheny Science & Technology). In this capacity, Dr. Babson was responsible for all aspects of review planning and implementation.

WASTE-TO-ENERGY OVERVIEW

Historically, the concept of “waste to energy” (WtE) has referred to any of a number of highly mature technologies (e.g., incineration or anaerobic digestion [AD]) utilized as a means to decrease waste volumes. Landfill capacity scarcity, coupled with increasingly stringent disposal regulations, necessitates novel waste-management solutions. In particular, the notion that waste streams represent valuable feedstocks for the production of biofuels and bioproducts is gaining currency. Conversion of feedstocks such as inedible fats and greases, biogas from landfills, dairies, wastewater treatment plants, and the organic fraction of municipal solid wastes into renewable natural gas, diesel, and aviation fuels is just beginning to gain market traction and represents a significant opportunity for additional expansion.

While there are advantageous market and policy factors unique to these feedstocks, they are subject to significant compositional, geographic, and temporal variability. This variability creates unique challenges and requires conversion technologies that are tailored towards particular families of feedstocks. In essence, the technologies need to go to the feedstocks, rather than the other way around.

Projects reviewed in the WtE session included hydrothermal liquefaction (HTL) and other conversion possibilities for both wet and gaseous feedstocks at a wide variety of technology readiness levels (TRLs), as well as analysis projects crucial to understanding the contexts in which these putative technology deployments would occur.

In the end, these feedstocks could comprise a relatively low-cost option that simultaneously solves currently existing disposal problems.

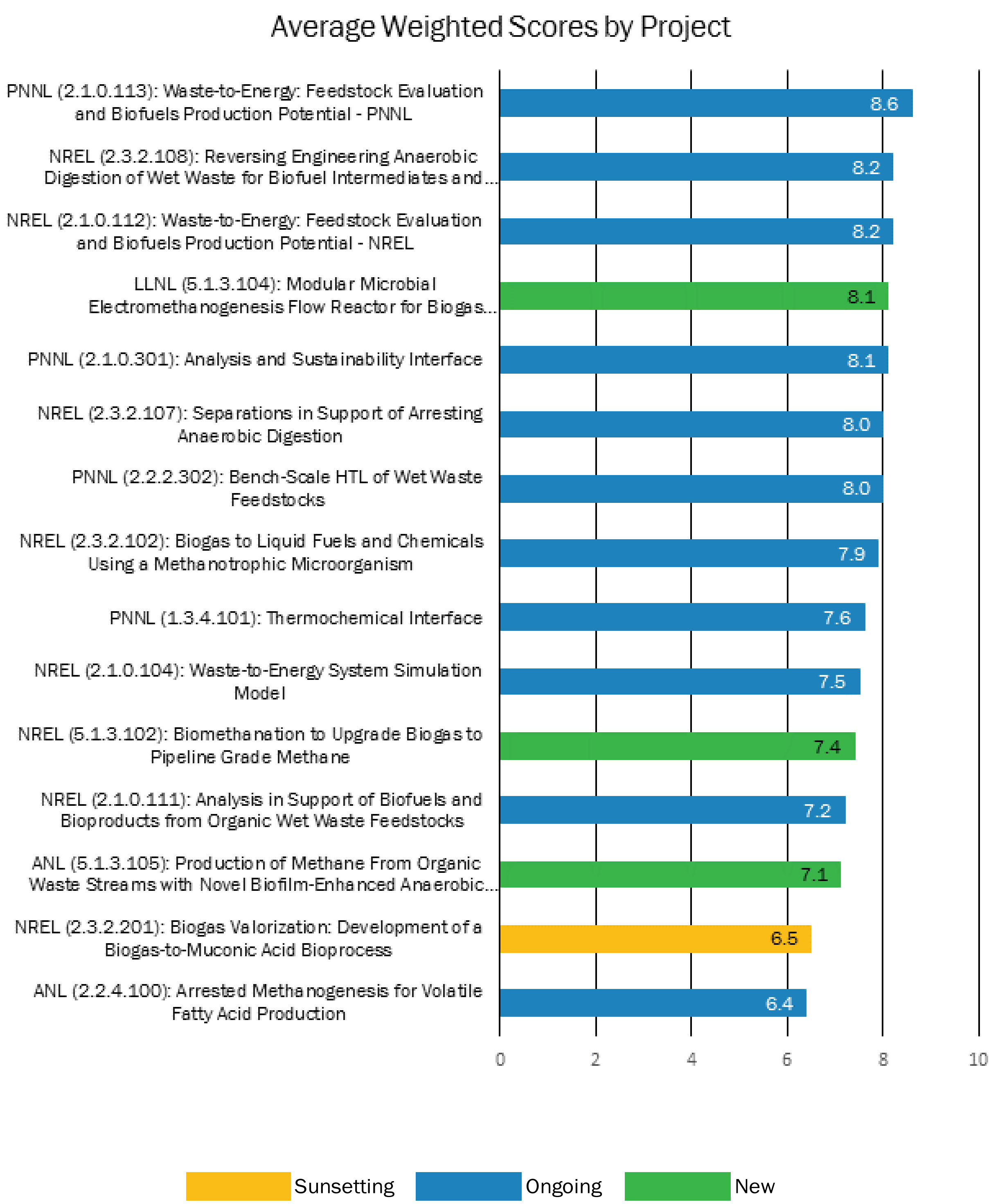
WTE REVIEW PANEL

The following external experts served as reviewers for the WtE Technology Area during the 2019 Project Peer Review.

Name	Affiliation
Phil Marrone*	Leidos
Lucca Zullo	VerdeNero, LLC
Gary Vanzin	Colorado School of Mines
Tim Olson	California Energy Commission

* Lead Reviewer

TECHNOLOGY AREA SCORE RESULTS



WTE REVIEW PANEL SUMMARY REPORT

Prepared by the WtE Review Panel

The WtE session that was reviewed at the 2019 Project Peer Review meeting contained a total of 15 projects. This was almost double the number of projects reviewed at the previous meeting in 2017, which was the first appearance of this session title. This report summarizes the main observations, thoughts, and suggestions of the review panel members with respect to the session as a whole. More detailed and specific comments on each project can be seen in the individual project reviews later in this section.

While the concept of WtE and associated technologies are not new, it has been only in recent years that BETO has included this area in its technology portfolio. A workshop held by BETO in June 2016 at the National Renewable Energy Laboratory (NREL) helped to initially identify the potential for energy extraction from wet and gaseous wastes with respect to available feedstock and conversion technologies. Using the resulting report *Biofuels and Bioproducts from Wet and Gaseous Waste Streams: Challenges and Opportunities* as a basis, BETO began a more formal research focus in the area of WtE. The first dedicated session of WtE at a peer-review meeting was in 2017, and the number of projects has grown considerably in 2019, as stated above. Though currently limited to projects involving wet wastes and biogas (itself derived from AD of wet wastes) feeds, the attention now being given by BETO to WtE feedstocks and conversion technologies has been long overdue and is a welcome addition to BETO's research efforts.

The biggest challenge to most renewable energy technologies is not technical achievement but economic viability, especially in the face of conventional, fossil-based technologies that enjoy incumbent advantages. The overall feedstock and production cost of renewable fuels and chemicals is captured in the projected selling price, typically denoted by BETO as the cost per gasoline gallons equivalent (GGE). The current goal is to develop technologies for drop-in biofuels that have a cost of $3/GGE. Since this goal is currently a challenge for most renewable energy technologies, the developmental focus needs to be on identifying and utilizing every cost advantage possible. Some of the most promising ways to achieve this are to: (1) utilize feedstocks that have a neutral or negative cost (i.e., don't have to be grown or purchased), (2) use conversion technologies that are compatible with the feedstock (i.e., involve minimal operations or steps), and (3) use conversion technologies that utilize as much of the feed composition as possible and recover as many high-value products as possible. Waste materials are the best example of satisfying the first option of neutral or negative cost and is why WtE is an important addition to BETO's portfolio. Eliminating the cost of feedstock growth and/or purchase can have a huge impact on reducing the overall cost of biofuel or bioproducts generation. Aqueous-based conversion technologies, such as hydrothermal processes and digestion, used in conjunction with wet wastes are excellent examples of ways to satisfy the other two options for minimizing costs. Unlike first-generation or more conventional processes, which require expensive drying of the feedstock and/or extraction of only certain components, hydrothermal processes and digestion utilize all of the feedstock and perform the necessary conversion reactions in water or a wet environment.

For all of the above reasons, the choice of wet wastes as part of BETO's initial foray into the field of WtE is an excellent start, and the particular focus on aqueous-based conversion (e.g., hydrothermal) and product-enhancement (e.g., biomethanation, arrested methanogenesis, biogas-to-liquid) technologies for use with wet wastes makes sense. The parallel support effort by BETO in modeling the availability and distribution of the most common wet-waste feedstocks (e.g., manure, food waste, wastewater sludge) is also a wise investment and helps guide and improve technology development for processing these wastes.

Yet despite this logical start with wet wastes and derivative products, BETO needs to expand its efforts in the WtE field to include more diverse types of waste. Municipal solid waste (MSW), or at least the organic fraction of MSW, represents a much larger potential feedstock and source of carbon that is currently being underutilized. As a waste, it carries the same potential benefits of neutral or negative cost that, with the right conversion technology, can be converted to fuels, chemicals, and/or power. Along with MSW recycling, research into technologies that can convert plastic waste into useful products would solve longstanding issues on waste reduction (both diversity and mass) while possibly lessening geopolitical issues around the longevity of plastic waste. BETO appears to recognize the value of this next-step expansion of WtE to include a broader definition of wastes based on future efforts outlined during several of the plenary talks at the 2019 Peer Review meeting. It is also encouraging to see mention of future work that includes more than just wet wastes in some of the current WtE projects (see, for example, the Waste-to-Energy: Feedstock Evaluation and Biofuels Production Potential project). This review panel strongly supports this effort by BETO to expand its focus on WtE to include a wider range of waste materials beyond just wet wastes.

IMPACT

In general, this review panel believes that all of the projects reviewed are relevant to BETO's mission and are having or promise to have a meaningful impact in the WtE field. While some projects may be more successful than others, all are providing valuable information to collectively advance the state of technology (SOT) for WtE. The achievements demonstrated to date justify further support by BETO of these WtE technologies. If anything, BETO should, in fact, expand its focus to include a more diverse source of waste materials as discussed above.

Of particular importance to note is the work on HTL for conversion of wet wastes to biocrude oil. This technology is a good example of what can be achieved when a process is paired with the right feedstock. The use of a water-based HTL technology is ideal for processing high moisture feeds because it avoids the significant cost of both drying the feed and having to chemically or physically isolate a specific feed component such as lipids. When the wet feedstock is also a true waste (i.e., having a negative cost), such as wastewater sludge, the cost benefits are further enhanced, making the technology even more attractive to potential industrial or commercial users. In light of this, as well as when considering the demonstrated biocrude yield values, it is not that surprising to see that associated modeling efforts have shown HTL as coming the closest to achieving BETO's fuel dollar-per-GGE goal. Despite its achievements, however, HTL technology is at a point in its development where its potential has been fully demonstrated at the research level but not yet at the commercial scale where industry finance is ready to step in. Further support by BETO at pilot scale is necessary for HTL technology to achieve its full potential and bridge the so-called "valley of death" with respect to process funding and development.

Another example of particularly impactful work in the WtE session is represented by the modeling-based projects. The resource modeling projects are performing an exhaustive yet essential task in collecting and organizing wet-waste feedstock quantity, location, and cost data down to a regional level. This information is critical to the development of the WtE industry. Other projects focus on techno-economic analysis (TEA) work in parallel with associated experimental-based projects in either HTL or arrested AD. The concept of using a TEA model fed by the latest experimental data to in turn predict key economic indicators and identify variables to explore further in subsequent experimental work for cost or performance optimization is a brilliant way to maximize research efficiency. The results of the modeling work help drive and direct experimental research, which then in turn feeds new and more accurate iterations of the model. System dynamics-based modeling is innovative and helps provide WtE industry performance and behavior over long-term periods. Taken together, the modeling projects play an important role and are having a significant effect on the development of WtE technologies.

One more example of projects having a notable impact are several that are focused on converting relatively low-value biogas to higher-value liquid chemical products (e.g., organic acids). This is a strategy that many renewable technologies have employed to help become economically viable, which is consistent with the options for maximizing cost advantages discussed above. By generating chemical species that have a high market demand as products or chemical intermediates, the resulting higher selling price helps offset the production cost more than the price that a liquid or gaseous fuel could command. The projects in this WtE session use different approaches to upgrading biogas (e.g., arrested methanogenesis or genetic engineering of microbes), and as exhibited by the attempt to generate muconic acid, success is not always guaranteed. Further, not all products chosen (e.g., volatile fatty acids) may command a high enough price to justify this approach. However, all of this work is providing valuable lessons learned that future work can build upon. Continued efforts at developing pathways to upgrade fuels to higher-value chemicals is therefore encouraged.

INNOVATION

Most of the projects reviewed in the WtE session have demonstrated some innovative aspects, whether in equipment design, materials used, and/or technical strategy/approach. The use of HTL technology to process wet wastes seems intuitive from a purely technical perspective but is innovative when one considers how long it has taken BETO to recognize its potential. Previous approaches for processing wet feedstock such as algae involved an elaborate effort to genetically modify the algae to produce high quantities of lipids. These lipids would then have to be chemically or physically extracted after first drying the algae before one could start processing into fuel or chemicals. In light of this background, the use of a water-based technology that utilizes all of the feed biomass is refreshingly innovative.

Several projects have developed innovative reactor designs. In particular, the microbial electrochemical reactor for biogas upgrading is a unique combination of microbial electrosynthesis biology with advanced materials for electrodes in a compact concentric cylinder design that allows a higher electron density and minimizes mass-transfer issues. Similarly, the 3D-printed scaffold design for biologically mediated biogas-to-liquid reactions (muconic and succinic acids) represents a novel design that has shown improved performance and mass transfer relative to the more traditional stirred tank reactor. Several projects also discussed a focus on modularity in design, which is good foresight with respect to future ease of scalability.

The resource-modeling projects are using innovative approaches in their attempts to quantify domestic sources of wet wastes down to the regional level. The overlaying of various categories of spatially based data to identify optimal locations (i.e., "hotspots") with respect to these feedstocks for placement of conversion technologies is particularly valuable. The future focus of these resource-modeling projects on potential feeds, beyond just wet wastes, is an encouraging sign that BETO is beginning to look at tapping into the much wider range of wastes that are available as potential feedstocks. However, the current lack of inclusion of any project with innovative conversion technologies for use with wastes such as MSW represents the most notable area missing from this WtE session.

SYNERGIES

Identifying and exploiting synergies that exist among individual projects is important for maximizing efficiency with respect to use of BETO's limited funds. There are several examples of project synergies in the WtE session that can be seen and are benefiting the projects involved considerably. The relationship between the experimental and modeling projects associated with the Pacific Northwest National Laboratory (PNNL) HTL technology and the NREL and Argonne National Laboratory (ANL) arrested AD technologies stand out as excellent demonstrations of project synergies. The experimental projects provide data for the modeling projects. The modeling projects then use the experimental data to validate TEA models and identify key variables via sensitivity analysis that have the biggest impacts on cost projections. This information then gets fed back to the experimental projects, which use the TEA results to plan future experiments focusing on these key variables, repeating the cycle. By directing resources to the variables that have the largest impact, one should, in theory, be able to get the maximum production cost reduction in the shortest time.

While it is one thing to set up this relationship on paper, in reality there is no guarantee that the interactions between the experimental and modeling groups will work as planned. It is therefore encouraging to see that the synergistic relationship described above appears to be working well for the PNNL and NREL groups. For example, identification of heat exchanger designs and ammonia removal costs as being significant HTL variables has led in turn to experimental work to better understand heat transfer coefficients for more efficient design and methods of ammonia removal from the aqueous product. Even the resource assessment models and system simulation model have provided useful data for the HTL experimental teams through economic comparisons to other technologies. Though not as far along as the HTL projects, the modeling effort associated with arrested AD has identified separation efficiency and minimum volatile fatty acid (VFA) product titers for the experimental groups. BETO should do all that it can to support the synergies that are evident among these projects and use the relationships demonstrated in these projects as a model to encourage similar production among experimental and modeling teams in other areas.

The NREL arrested AD experimental effort is itself an example of good synergy between two groups that have divided the work into the biology research and downstream VFA separations research. To make this technology viable, the two very different challenges of biologically stopping the digestion (i.e., methanogenesis) process at the acid production point and subsequently removing these acids from the digestion medium must both be optimized in an integrated continuous system. Conducting both lines of research separately but in parallel generates synergies that should help both areas of research.

While taking advantage of synergies among projects is essential, there is a fine line between project synergies and duplicated efforts. Among projects that focused on the same general technology, it was not always initially clear how the projects differed from each other and what made each one unique. In the future, this review panel feels that it would be helpful if each project were required to explain upfront how it is distinct from other related projects and what makes its work unique. Even better would be if a BETO representative at future peer review meetings could address the project's uniqueness and why it was initially awarded funding as part of its normal introduction of each project presentation.

FOCUS

All of the projects in the WtE session involve appropriate and representative technologies for this topic. As pointed out earlier, however, the projects in this session deal with a more specific subset of WtE (i.e., wet wastes) than the session heading name implies. This review panel recommends that BETO do one of the following to correct this mismatch: (1) change the name of this session from "Waste-to-Energy" to "Wet-Waste-to-Energy" to more accurately reflect the intended focus, or (2) expand the number of projects in this session to include a greater diversity of waste feed types (the latter being the option preferred by this review panel). Several projects have already stated an intent under future work to explore the use of waste plastics or the organic fraction of MSW as a feedstock, which should be encouraged by BETO. It is also encouraging (and timely) to see BETO specifically call out the topic of "Renewable Energy from Urban and Suburban Wastes" in its most recently announced Fiscal Year (FY) 2019 Bioenergy Technologies Office Multitopic Funding Opportunity Announcement (FOA) (DE-FOA-0002029) in May 2019. This is clearly a step in the right direction to better utilize a greater quantity and variety of waste resources.

In the process of increasing the diversity of waste types as feedstock, BETO should, at the same time, narrow its definition of acceptable wastes for this session to be those materials having a negative or near-neutral feed cost. This is a simpler yet accurate definition of a waste in the specific context of BETO's objectives. Waste feedstocks that meet this definition will have an overall reduced process cost for conversion to fuels or chemicals relative to feedstocks that must be grown, harvested, and/or purchased. As a result, these materials allow the best chance that the product(s) can meet BETO's target fuel production cost, and thereby maximize the potential return on limited research dollars.

Back on the topic of wet wastes, one area in the WtE portfolio that could benefit from additional emphasis is additional hydrothermal conversion technologies. As has been pointed out earlier, HTL has a number of advantages for processing wet wastes. HTL also generates a liquid fuel product, which is consistent with BETO's preferences and justifies the funding provided to date for the development of this technology. However, there are other forms of hydrothermal processing that may be worth supporting, either in addition to or in parallel with HTL, depending on the specific application. These other types of hydrothermal conversion technologies have similar advantages to HTL but differ in the particular process conditions and therefore the spectrum of products generated. Baseline technical and economic evaluations of expanded hydrothermal technologies could include supercritical water gasification and hydrothermal carbonization (HTC).

Supercritical water gasification generates hydrogen gas as its major product, but with an appropriate catalyst, the major product can be changed to methane under either supercritical or subcritical conditions. HTC produces solid char (or biochar) as the major product, which has many potential uses such as fuel, soil enhancer, etc. BETO support for further development of these related hydrothermal technologies should be considered for inclusion in the WtE portfolio along with HTL to provide for a more diverse set of fuel and chemical products. The best hydrothermal technology or technologies to use in any situation ideally could then be chosen based on the specific needs, constraints, and economics associated with each potential application.

TECHNOLOGY DEVELOPMENT PIPELINE

Taking an innovative concept and proving that it can succeed at the bench scale is of course a necessary and important step in the process of new technology research and development (R&D). Funding these types of projects is something that BETO has and continues to do very well. However, funding up to the proof-of-concept point is not enough for most technologies to attract sufficient private funding in their commercial development. There are usually significant unknowns associated with scale-up that keep investors wary. Abandoned by government funding but not yet able to secure private funding, this is the infamous "valley of death" referred to earlier which many otherwise promising technologies have not succeeded in passing. BETO can and should play a role in helping good technologies bridge this economic chasm by funding more pilot-scale projects. While not taking away from funding traditional R&D, BETO should also consider funding projects that demonstrate operation of continuous, integrated, pilot-scale systems of conversion technologies to generate the long-term operating and maintenance data that private industry and investors need to see before their inherent skepticism and risk aversion may be overcome.

It is encouraging to see that several projects in the WtE session are already moving in this direction. PNNL has built and operated its own pilot-scale HTL system and is participating in another BETO-funded team project that will be testing a commercially designed HTL pilot system at a wastewater treatment plant (though this latter project is part of the Advanced Development and Optimization session). The ANL arrested AD project intends to test a 200-gallon-sized version of its anaerobic membrane bioreactor (AnMBR) for VFA production in the coming year as part of its project. The NREL project on biogas upgrading not only has operated at large scale (700 L) but also plans to build a 30-L-capacity mobile version of their technology in their project. Where appropriate, mobile versions of conversion technology systems are another good way to demonstrate operation at scales of commercial interest and to bring the technology directly to an industrial site or feedstock location for further visibility. While none of the above is new or in disagreement with BETO's past funding philosophy, recent actions by DOE at the direction of the current administration suggest a retreat to focusing solely on research-scale projects, and this is of concern. This review panel therefore feels it necessary to emphasize the continued importance of funding pilot-scale projects to help new technologies fully complete their successful transition to qualifying for commercial lending and funding.

Of the existing projects in this session, some aspects of the biomethanation and arrested AD projects may require additional attention. For biomethanation, more focus on how to recover the dissolved methane from these aqueous systems is needed, because this is not trivial or easy. In arrested AD, focus is needed on demonstrating long-term operation of these systems regardless of the type of reactor chosen. This will be challenging because of the unknown behavior of the genetically modified microbial consortia over time, the use of a heterogeneous carbon and energy source, and the possibility of end-product inhibition. A more complete fundamental understanding of the microbial consortia and the impact of arresting the methanogenesis reaction is needed, along with a better understanding of feedstock and metabolite composition changes during the process.

Most of the projects in the WtE session discussed the inclusion of one or more collaborators, partners, or advisors from private industry that are on the project team. This is a smart strategy with respect to technology development for several reasons. Having industrial input to a project helps provide guidance and a sanity check for the direction of research so that the technology is developed in a way that will be most useful to the potential end users. It also allows the research team to tap into valuable knowledge and resources in the industrial community for more efficient use of time and funding. The flow of information, however, is not just one way. Having industry personnel as team members also helps keep industry apprised of research results and engaged in the research process, thereby generating awareness and hopefully interest in future development as the technology matures. This policy is a win-win for everyone and is therefore an essential aspect of BETO's project management that should be encouraged in all current and future projects.

RECOMMENDATIONS

The recommendations for further improvement of this WtE session as submitted by this review panel are as follows:

- Expand the WtE session to include more diverse waste feedstocks, including MSW. Alternatively, if BETO specifically wants to focus only on wet wastes or their derivatives, as is the case now, this session should be renamed to "Wet-Waste-to-Energy" to reflect the intended feedstock more accurately.
- Encourage the use of neutral or negative cost waste feedstocks in current and future projects in this session. Along with matching the feedstock to the appropriate conversion technology (e.g., water-based technology for wet wastes), this will provide the best opportunity to minimize unnecessary fuel (or chemical) production costs, optimize process economic viability, and meet the target BETO fuel selling price of $3/GGE.
- Increase funding for pilot-scale development of sufficiently promising conversion technologies to help bridge the "valley of death" with respect to commercial maturity. The continued support beyond bench scale is important to demonstrate acceptable performance, provide critical operating data, and reduce technical risk at a scale where private industry and lending institutions are more likely to be willing to take over with further commercial development of the process. This additional investment by BETO also increases the chance that the total investment made by BETO in a technology from the start is not ultimately wasted.

Though not specifically related to the WtE program, the following recommendations for both BETO and researchers are also offered to improve the presentation format and associated review:

- BETO staff should provide a brief introduction prior to each presentation that includes the original rationale for the project choice for funding and what makes each project unique from or related to others in the session on the same general topic.
- Both the baseline status of the technology being investigated at the start of the project and the impact of the project results presented on the overall commercialization timeline should be stated in each presentation (i.e., describe where you started and where you are now with respect to commercialization). This information will help reviewers gauge both the degree of progress made and how far away the technology is from being market ready.
- Repetitive (i.e., the same in every project) and less-useful information with respect to technical evaluation (e.g., management approach) should be eliminated from the presentations to allow more time and space for technical content. This is not to say that this information is not important for BETO to gather, only that it does not need to be included in the technical presentations given the constraint of limited time and space.
- Statistics quantifying the stability and variance associated with key results (e.g., error bars) should be included wherever and whenever available.
- A list of acronyms used in each presentation should be required.

- For TEA, resource, and other modeling-based projects, a list of critical assumptions that underlie the results presented should be stated.

WTE PROGRAMMATIC RESPONSE

INTRODUCTION/OVERVIEW

The Conversion R&D Program Area would like to take the opportunity to thank the four WtE reviewers for their time and careful review of the portfolio.

The review panel noted that the title of the session led to confusion with regards to the feedstocks being investigated across this session and elsewhere in the BETO portfolio. While this session was entitled “waste-to-energy,” it focused on wet-waste streams (municipal wastewater sludge, manure, food waste, fats, oils, and greases, and biogas derived from these streams). In future peer reviews, BETO will more explicitly explain which waste streams are/are not included in respective sessions given that the definition of waste can be very broad.

Related to this, the review panel discussed that technologies and projects related to the conversion of municipal solid waste were not represented in this session. Working on MSW is an emerging area of interest for BETO given that it is a highly heterogeneous stream and presents unique compositional and resource challenges. The program has already begun resource assessment to focus on nonrecyclable fractions of MSW, including plastics, paper, and construction and demolition wastes. BETO recently identified seven areas of particular interest in a report on ways to improve the economics of municipal solid WtE.[1] BETO has also issued several funding opportunity announcement topics directed specifically toward MSW and has issued a request for information on strategies for the utilization of food waste.

As the panel has identified, BETO concurs that technologies for converting MSW may be considerably different than those being explored within the wet WtE space. For example, HTL may be amenable to the food waste fractions of MSW but less well suited for other fractions therein. As with the Conversion R&D Program Area’s first forays into wet wastes, the program intends to guide the development of conversion technologies with resource assessment and TEA.

The following sections specifically address the top recommendations from the review panel:

Recommendation 1: Expand WtE to include MSW.

As discussed above, the program acknowledges that the title of this session was misleading because the projects presenting only covered a subset of wastes. In some cases, other waste streams (e.g. carbon dioxide [CO_2]) were explicitly covered in separate and parallel review sessions, and there are fractions of waste (e.g., food waste) that have not been explored to a considerable extent within the portfolio. The program has already begun to increase its activity with regards to strategy and utilization around MSW and would expect to have a number of projects that are targeting those streams. As discussed above, BETO will ensure that definitions of waste are clear to avoid this confusion.

[1] Bioenergy Technologies Office. 2019. *Waste-to-Energy from Municipal Solid Wastes*. Washington, D.C.: U.S. Department of Energy. DOE/EERE-1796. https://www.energy.gov/sites/prod/files/2019/08/f66/BETO--Waste-to-Energy-Report-August--2019.pdf.

Recommendation 2: Encourage the use of neutral or negative-cost feedstocks.

The program concurs that the utilization of zero- or negative-cost feedstocks presents a unique set of opportunities for moving technologies from bench and pilot scale into the market and simultaneously meeting office cost target objectives. In many cases, these feedstocks represent an environmental and cost liability to the producer or company managing, which presents a unique and attractive value proposition. To this end, analysis efforts in the WtE portfolio of projects have begun conducting "hot-spot" analyses to identify these opportunity areas and which might represent opportunities for first-of-kind facilities. While not presented in detail during these sessions, these areas tend to have shared attributes such as dense populations, organics diversion regulations, and/or limited landfill capacity, amongst others. The program will continue to encourage that these analyses be published and shared with both municipalities and with technology providers.

The program also appreciates the comment to appropriately match the feedstock to the conversion technology. To this end, HTL has been a technology of particular interest given that it is amenable to high-moisture feedstocks and can convert a diverse composition into a more homogenous TRL, and the program has sought to explore multiple solutions in parallel as a risk-mitigation strategy. For example, this has been the strategy with the arrested AD projects. As resources allow, the program continues to explore additional technological solutions for these wet wastes that are guided by TEA and move towards clear technical targets such as waste conversion efficiency.

Recommendation 3: Increase funding for pilot-scale development and continue bench-scale development.

BETO fully concurs that it is critical to support technological development beyond the bench scale and into pilot scale. There are many technological R&D barriers that cannot be solved, and in some cases identified, until a technology has been scaled up or integrated with other upstream and downstream unit operations. Overcoming these integration and scaling challenges is a key objective of the Advanced Development and Optimization (ADO) Program Area. As resources allow, BETO is committed to funding projects beyond the bench scale to ensure that technologies are at a risk level that enables them to move into the market.

To date, the program feels that HTL is the only wet WtE technology within its portfolio that achieved a sufficiently high TRL to scale up. As such, the ADO Program funds pilot-scale research on HTL to address scaling and integration barriers. Simultaneously, the program has continued to support the bench-scale R&D work on this technology to respond to barriers identified at a larger scale and to continue to optimize process parameters in a cost-effective way.

The program recognizes that there are ways to improve the collaborations between the bench-scale and pilot-scale researchers and improve the coordination within BETO. For technologies that achieve the requisite technological maturity, the program is working to formalize the interface between the Conversion R&D Program, ADO Program, and other BETO programs as appropriate. These could include joint project milestones, coordinated technical targets, harmonization of TEA and life cycle assessment (LCA) assumptions, and most importantly to identify which barriers and technical problems are being addressed at which scale.

THERMOCHEMICAL INTERFACE

Pacific Northwest National Laboratory

PROJECT DESCRIPTION

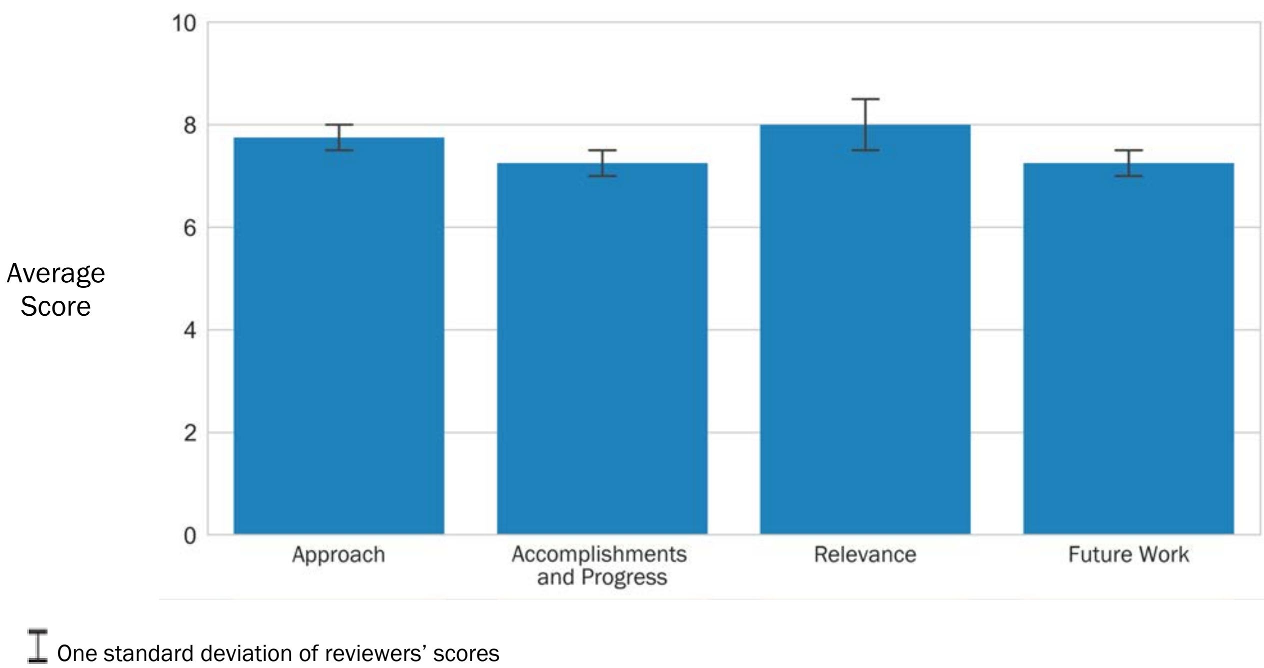
WBS:	1.3.4.101
CID:	NL0026324
Principal Investigator:	Mr. Dan Anderson
Period of Performance:	4/1/2014–9/30/2019
Total DOE Funding:	$4,860,000
DOE Funding FY16:	$1,520,000
DOE Funding FY17:	$1,200,000
DOE Funding FY18:	$1,390,000
DOE Funding FY19:	$750,000
Project Status:	Ongoing

Most studies on microalgae HTL are currently conducted in small laboratory batch reactors with a few research teams reporting on continuous systems. Scalable designs and strategies for optimal algal HTL configurations require data for nutrient recovery, water treatment and recycling, enthalpies of HTL reactions, residence times and space velocities, heat recovery, corrosion, separations, and removal of heteroatoms (i.e., upgrading to hydrocarbons). In addition, variations in seasonal algal cultivation require approaches to capital asset utilization and balancing of energetic tradeoffs associated with feedstock management and storage. Benchmarking how these technical issues impact the costs of algal HTL conversion and tracking how improvements reduce capital and operating costs are a responsibility of BETO.

The project team at PNNL has more than five years of experience with continuous algal HTL systems and is developing advanced HTL processing methods to improve process efficiency and reduce capital and operating costs for the production of drop-in biofuel blendstocks from microalgae. One strategy for achieving full utilization of capital assets (and minimizing operational costs) is to blend algal feedstocks with woody materials during lean algal seasons. The project is developing methods for coprocessing algal/woody feedstock blends and has identified synergistic effects beyond what was expected.

Weighted Project Score: 7.6

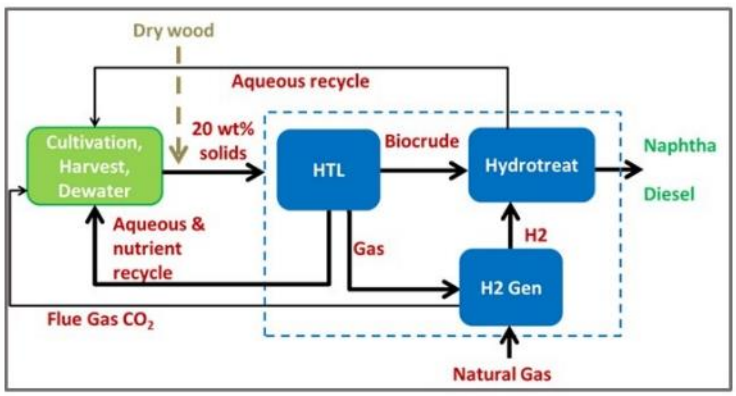
Weighting for Ongoing Projects: Approach - 25%; Accomplishments and Progress - 25%; Relevance - 25%; Future Work - 25%



Upgrading technology for the production of finished fuels blendstocks is a critical subtask of the project, as are studies of nutrient recycle from HTL waste streams for algal cultivation. A major accomplishment so far includes demonstration of recycling HTL byproduct streams to supply 100% of the nutrients required for algal cultivation, with 89 culture cycles completed by Q4 of FY 2018.

In recent years, the project supported the acquisition and testing of an engineering-scale HTL process development unit at PNNL with three skids for (1) feedstocks prep, (2) HTL processing, and (3) product separations. All data from bench- and engineering-scale HTL efforts feed directly into algal HTL process models for examining TEA and LCA impacts of different system configurations. The process models inform BETO's annual SOT evaluation and are also used to determine the most useful R&D targets for driving down fuel costs.

Current Algae HTL Conversion Process



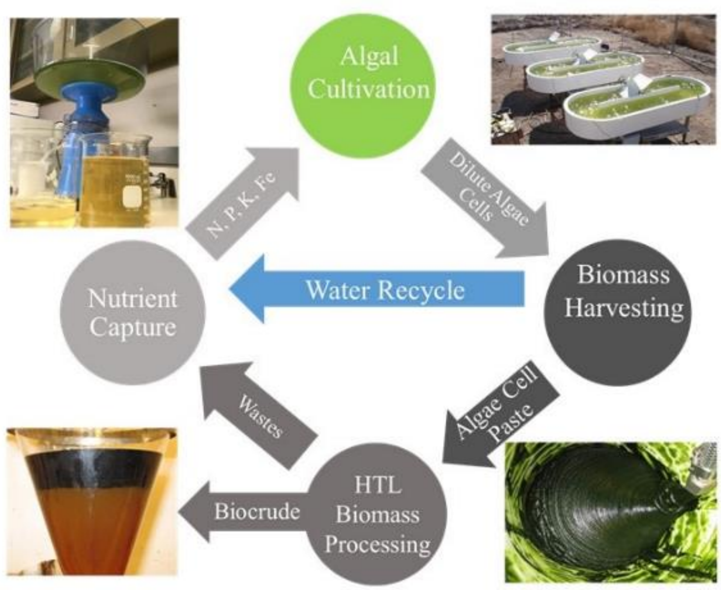


Photo courtesy of Pacific Northwest National Laboratory

OVERALL IMPRESSIONS

- This project demonstrates further progress in optimizing HTL process technology with the goal of meeting BETO's liquid biofuel cost target. Results achieved over this review period have shown how increases in feed solids loading for biocrude production and pretreatment and an improved catalyst for upgrading are helping to drive down the overall cost towards the BETO goal. PNNL staff have continued to investigate methods of improvement to the HTL process from many angles, as shown by the results of blending tests and nutrient recycle tests. While it is understood that the HTL algal work has laid the groundwork for subsequent tests with real wet wastes (e.g., sludge), the algae used in these tests are not waste and therefore this project may not really belong in this group (although this is a BETO decision). However, eutrophic algae would qualify as a waste and its negative feedstock cost would further help meet the BETO biofuel cost target, so it should be considered as a future feedstock. The only major concern with the work shown is the apparent disconnect in the modeling cost results between that shown in this project and in the formal TEA modeling project (2.1.0.301), also performed by PNNL staff. Future modeling work in any of the PNNL HTL projects should all be performed on the same basis with the same cost categories to avoid confusion.

- This is a relevant project and HTL has tremendous potential given the wide applicability to feedstocks that are not easily or economically amenable to other treatments. I would like to see a bit more detail on the choice of feedstock and feedstock blends. The focus on the recycling of water and recovery of nutrients is very good. This being said, the technical and economic feasibility of upgrading by hydroprocessing remains a critical unknown and the weakest link in the TEA, even accounting for the future work. HTL may be the only practical thermochemical technology working with wet streams.

RECIPIENT RESPONSE TO REVIEWER COMMENTS

- We thank the reviewers for their thoughtful comments. This project is part of the Advanced Algal Systems Program at BETO, specifically focused to develop an HTL conversion pathway for algal biomass to produce biofuels. We do agree that the placement of this project in the WtE Program Review and not in Advanced Algal Systems Program Review may have resulted in some confusion for WtE reviewers. On the positive side, we were able to show the reviewers how this algal HTL project had laid the technical groundwork for establishing the HTL conversion and modeling projects focused on wet wastes. However, there was a disconnect with the algae project and its relationship to the wet-waste process/TEA because the associated algal HTL process model project was reviewed in the Advanced Algal Systems Program Session. This project has a direct connection with HTL algal model/TEA project from the very beginning, but it was not presented to the reviewers. So, there is direct connection between the algal HTL conversion project and the algal HTL modeling effort as the reviewers suggest. We do agree that focusing on eutrophic algae as a potential negative-cost feedstock makes sense and we are pursuing project opportunities in that area.

- Input from the NREL/PNNL resource assessments and the algal TEA/modeling team have driven the selection of the feed blendstocks we are testing (i.e., loblolly pine residuals and algae). Some pine plantations are located in the southern United States, close to the candidate locations for algal farms (e.g., Florida, Texas). Also, pine residuals have a relatively low moisture content and can be beneficially combined with more dilute algae, eliminating some of the dewatering requirement.

WTE SYSTEM SIMULATION MODEL

National Renewable Energy Laboratory

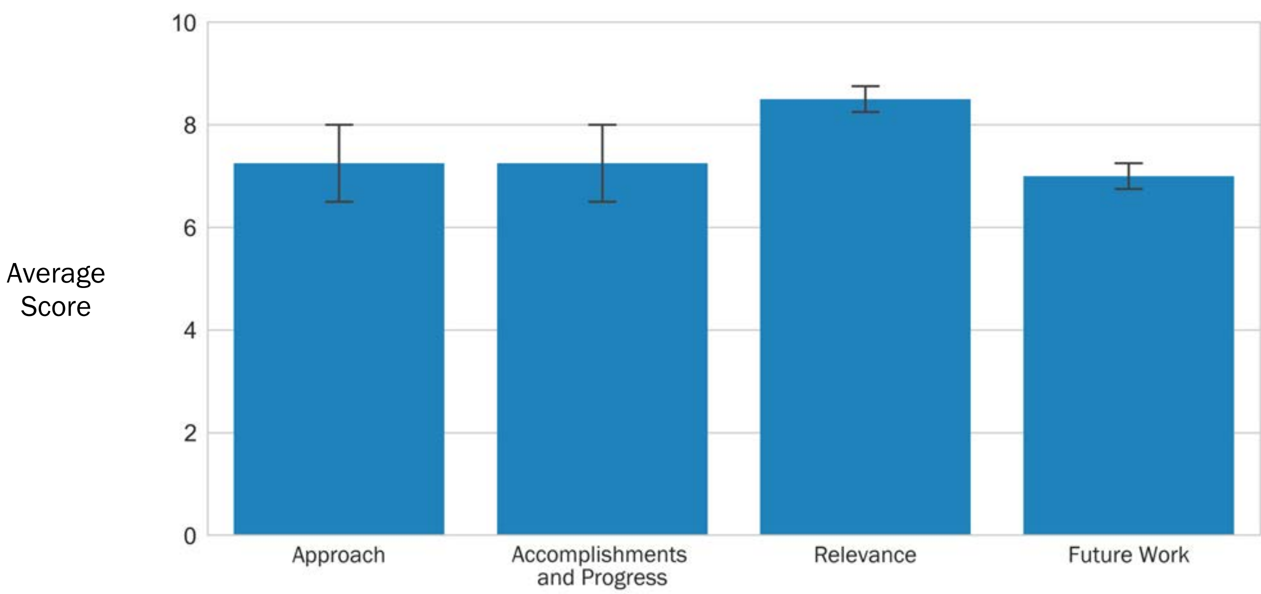
PROJECT DESCRIPTION

WBS:	2.1.0.104
CID:	NL0029525
Principal Investigator:	Dr. Danny Inman
Period of Performance:	10/1/2015–9/30/2020
Total DOE Funding:	$1,440,000
DOE Funding FY16:	$400,000
DOE Funding FY17:	$390,000
DOE Funding FY18:	$350,000
DOE Funding FY19:	$300,000
Project Status:	Ongoing

Leveraging existing waste from landfills, confined animal feeding operations, and publicly owned treatment works for energy and chemical production could add revenue to existing waste disposal treatment operations and contribute to high-level sustainability goals. Although these waste streams are readily available throughout the country, most of the current WtE projects only utilize biogas to produce electricity. Transitioning from the current status of disparate projects producing low-value energy to a cohesive industry optimized around producing fuels and chemicals from waste will require a systems approach to understand the impacts of external factors, internal feedbacks, and key levers and to maximize the impact of DOE efforts. The objective of this project is to perform systems analyses to elucidate the impact of policy, R&D, and techno-economics on the WtE system as a whole, as well as at specific points in the supply chain and for individual sectors (e.g., landfills, confined animal feeding operations, publicly owned treatment works). This project will leverage existing DOE models (e.g., the Waste-to-Energy System Simulation Model), along with current DOE techno-economic data, resource assessment data, and stakeholder input to perform analyses that are directly tied into BETO goals.

Weighted Project Score: 7.5

Weighting for Ongoing Projects: Approach - 25%; Accomplishments and Progress - 25%; Relevance - 25%; Future Work - 25%



One standard deviation of reviewers' scores

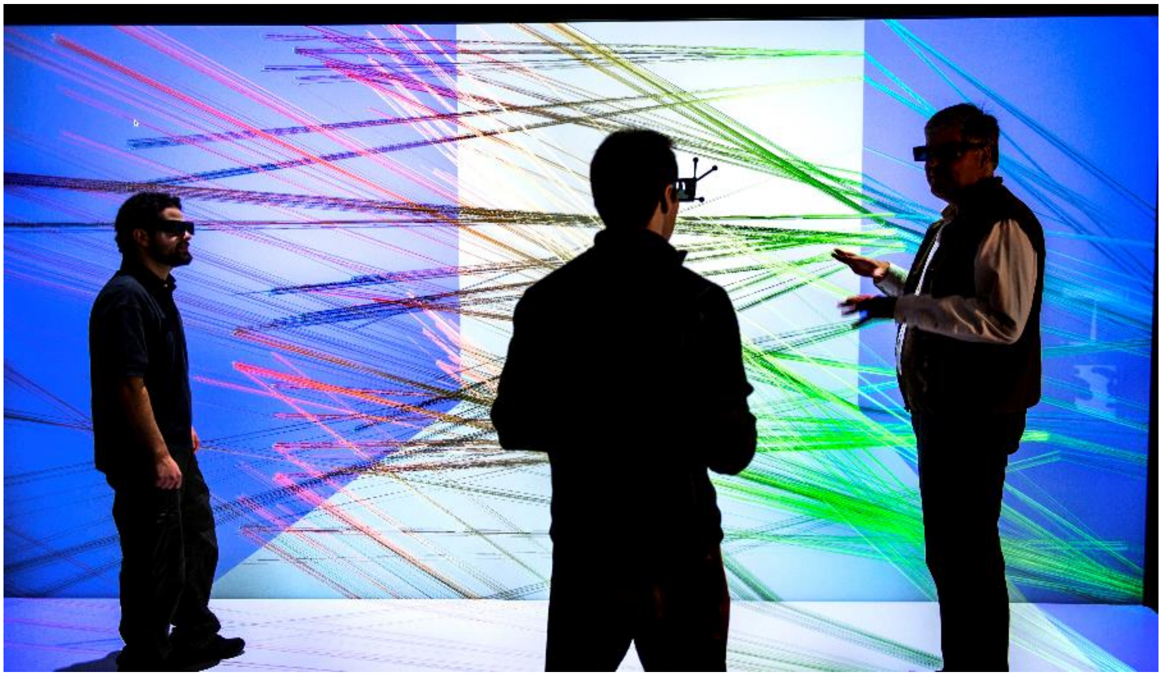


Photo courtesy of National Renewable Energy Laboratory

OVERALL IMPRESSIONS

- This project represents another important modeling effort to benefit the efficient development of waste-conversion technologies to energy, with this model aiding in predicting WtE industry performance and behavior over long-term periods. The systems dynamics approach is innovative and can provide interesting and valuable information on energy trends and nonintuitive results. Of course, one reason a result may appear nonintuitive is that it is incorrect. There is some concern as to how well the model predictions are able to be and have been independently validated, especially in trying to predict trends up to 20 years in the future. Explaining some of the operating philosophy of the model as well as key inputs and assumptions used would help better understand the basis for results presented and increase confidence in how these results are generated. The project would also benefit from a clear list of detailed tasks and a schedule to track progress.

- This presentation outlines a good project that tackles a challenging topic and attempts to gain insight by building a model sophisticated enough to capture all the key factors, yet simple enough to be manageable. The discussion about strengths and weakness is particularly difficult as one may be easily assumed or request exceedingly high standards or expect unrealistic accuracy. What may be seen as weaknesses for a predictive model used in the design become a natural feature in a model designed or used to support decision making and high-level analysis. With this in mind and realizing that this project mostly delivers the latter and not the former, I found this project of great interest and I would encourage the development to be continued in such a way to provide the most value to those engaged in that effort. I appreciate the PIs showing regional application as it also shows that it can likely be scaled further down the geographical scale. More precise quantification of intuitive insight is valuable, yet the model has not—at least in my view—delivered any significant counterintuitive insight as is often the case in systems dynamics.

RECIPIENT RESPONSE TO REVIEWER COMMENTS

- We thank the reviewers for their helpful and supportive feedback. We will incorporate these suggestions into our future workplans.

ANALYSIS IN SUPPORT OF BIOFUELS AND BIOPRODUCTS FROM ORGANIC WET-WASTE FEEDSTOCKS

National Renewable Energy Laboratory

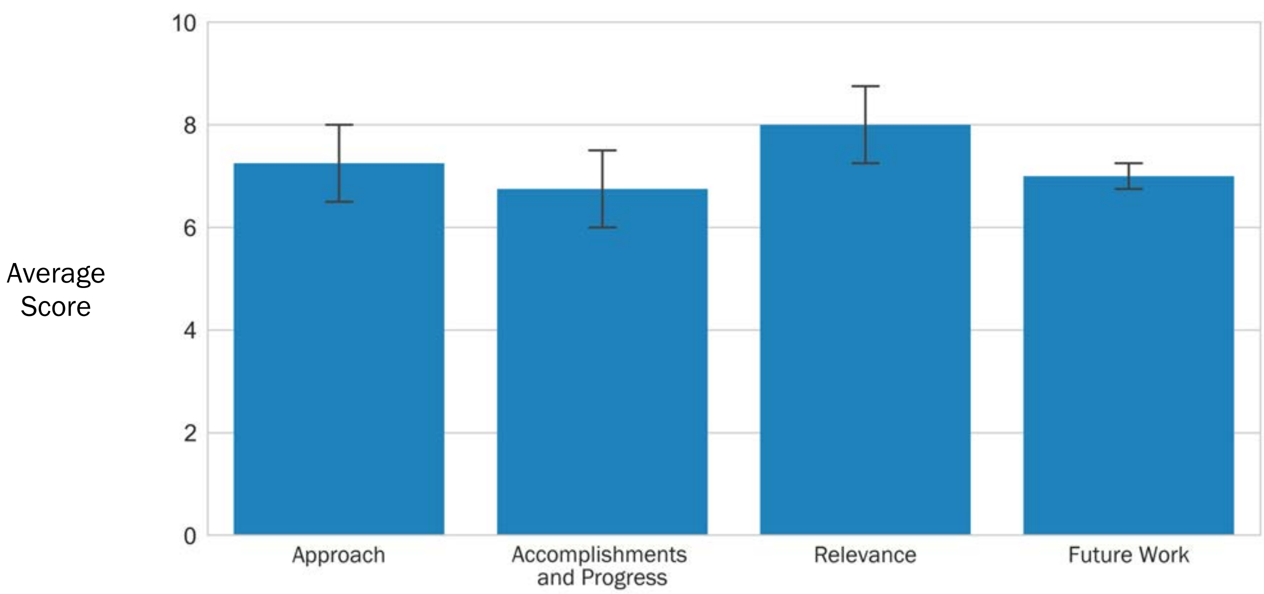
PROJECT DESCRIPTION

WBS:	2.1.0.111
CID:	NL0033389
Principal Investigator:	Dr. Ling Tao
Period of Performance:	10/1/2017–9/30/2020
Total DOE Funding:	$400,000
DOE Funding FY16:	$0
DOE Funding FY17:	$0
DOE Funding FY18:	$200,000
DOE Funding FY19:	$200,000
Project Status:	Ongoing

Total wet-waste feedstocks present an annual energy resource of 11.3 billion GGE, including wastewater residuals, animal waste, food waste, fats, oils, and greases. Conversion of wet-waste feedstocks into transportation fuels and chemicals not only represents a significant opportunity for additional expansion of transforming underutilized resources into a variety of value-added fuels and chemicals, but also reduces landfills. TEA is critical for guiding WtE pathways from R&D to widespread deployment. Thus, the goal of this project is to develop conversion-process design concepts and perform cost analyses to evaluate WtE opportunities to identify R&D needs and prioritization by BETO and industry. From FY 2018 to FY 2020, this project performs TEA to support three ongoing projects on biological conversion (arrested AD). The arrested AD produces higher-value fuel, chemicals, or their precursors by arresting methanogenesis while utilizing all organic substrates (carbohydrates, lipids, fats, proteins) in the waste feedstocks. At the end of the project, we will report identified key performance targets and understanding on potential economic viability to assist R&D prioritization decisions. We should also have a broad range of wet-waste conversion technologies investigated

Weighted Project Score: 7.2

Weighting for Ongoing Projects: Approach - 25%; Accomplishments and Progress - 25%; Relevance - 25%; Future Work - 25%



One standard deviation of reviewers' scores

for their economic and environmental sustainability potentials, offering opportunities to reduce biofuel and bioproduct production costs by converting cheap, readily available waste streams.

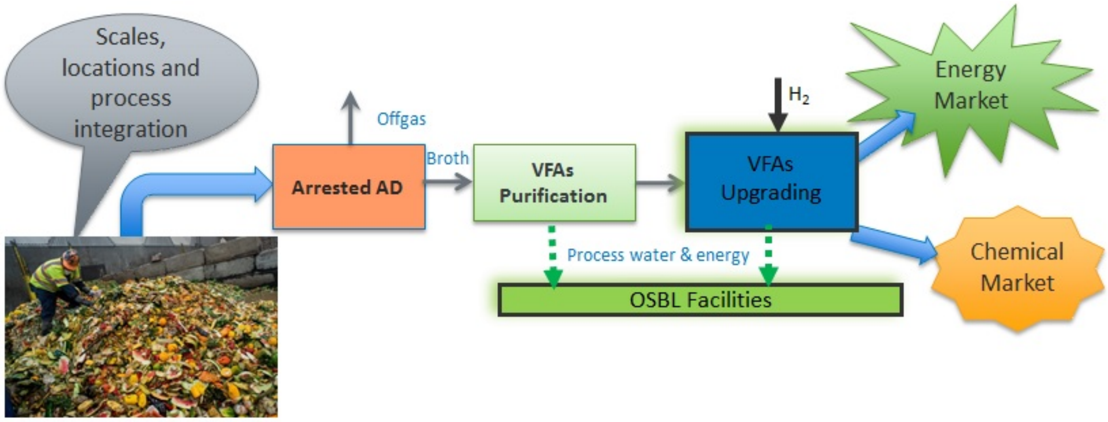


Photo courtesy of National Renewable Energy Laboratory
Note: OSBL = outside battery limits facilities

OVERALL IMPRESSIONS

- This project provides critical TEA modeling support to the three research projects devoted to developing the arrested AD process. By working closely with these experimental groups and with industry partners, this project will help assess whether the arrested AD process can be economically viable and what particular variables to focus on to achieve viability. Though it is not clear if the model has begun working with experimental data from the research projects yet, there has been an analysis of the base case of biogas production from conventional AD, which is a good comparison to have, as well as a theoretical assessment of performance metrics and energy yields for VFA product generation versus biogas. While the general direction of this project is sound and clear, how the project intends to implement its many activities is a bit vague. There needs to be a specific task list and schedule developed, along with prioritization of these tasks to ensure that as much of the intended work can be performed in the remaining time available and that efforts will be efficiently coordinated with the tasks and schedule of the research teams.
- I like the overall current and future framework. The critical support to the relevant projects—some of those in their review may have been judged as lacking in the TEA—makes this project very useful. The results thus far are not yet providing substantive novel insight, but I expect that to change. Product economics are weak; what are the commercial assumptions for the organic acids? Biogas economics seems skewed towards high prices, which need to be understood lest we provide a biased assessment of the alternatives.

RECIPIENT RESPONSE TO REVIEWER COMMENTS

- We thank the reviewers for their helpful insights and feedback. Our work is highly integrated with ongoing R&D efforts and with the overall BETO portfolio. Although we have not yet vetted experimental data into the TEA models, we have worked with R&D teams on developing the conceptual process design with all major unit operations, key process parameters for each operation, as well as process integration strategies. To improve input data quality for credible TEA results, we will solicitate feedback from expert stakeholders to seek assistance and industry-relevant input for validating the models, major assumptions, and relevant analysis data. In line with our project goals and approach, we will also perform sensitivity analyses and uncertainty evaluations on key cost drivers based on inputs from subject-matter experts from both industry and R&D teams. Although the focus of the current funding phase is to support and guide arrested AD R&D, the overall goal of this project is to develop defensible studies in support of the WtE platform by identifying R&D opportunities and economic and sustainability targets. By FY 2020, we will report key cost drivers, cost breakdowns, a value proposition over the current approach of disposing wet wastes, and a project path forward to achieve BETO's cost targets for fuels and chemicals. We will also report SOTs for all three projects with vetted research data.

WTE: FEEDSTOCK EVALUATION AND BIOFUELS PRODUCTION POTENTIAL – NREL

National Renewable Energy Laboratory

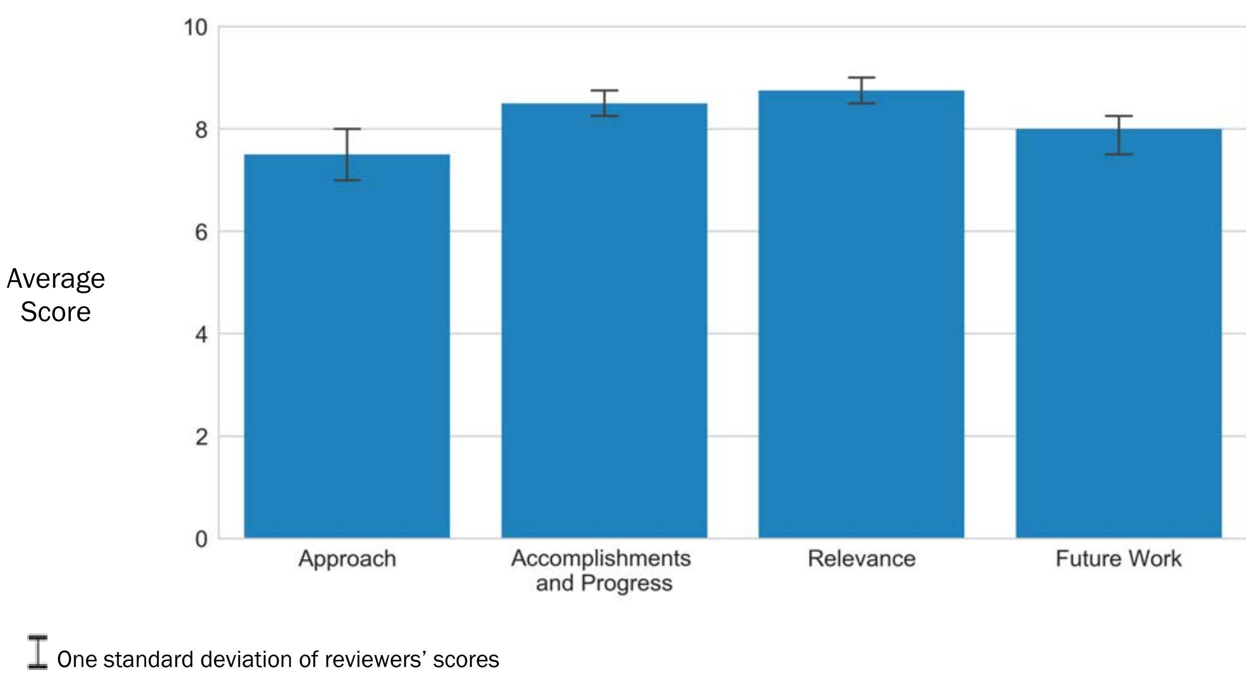
PROJECT DESCRIPTION

WBS:	2.1.0.112
CID:	NL0029526
Principal Investigator:	Ms. Anelia Milbrandt
Period of Performance:	10/1/2017–9/30/2019
Total DOE Funding:	$814,000
DOE Funding FY16:	$0
DOE Funding FY17:	$0
DOE Funding FY18:	$514,000
DOE Funding FY19:	$300,000
Project Status:	Ongoing

The goal of this project is to provide foundational data, strategic analyses, and modeling critical to the economic and environmental viability of the emerging WtE industry. The project 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 the population grows, and could present a niche opportunity for the bioeconomy of the future. Our approach is rigorous economic and geospatial modeling with input from key stakeholders. Accomplishments to date include: (1) a comprehensive estimate of wet WtE resource prices at the county level and national state supply curves; (2) preliminary results of a wet WtE resources "hot-spot" analysis; and (3) baseline, AD, and composting pathway models for cost-benefit analysis of food waste (preliminary results have been provided to BETO). Our estimate of wet WtE resource prices indicate that some portion of the feedstock exists at a negative price. If a resource has been commoditized (e.g. fuels, oils, greases [FOG]), its price is determined by market demand. If a resource is regarded as waste, its price is driven by the cost of its disposal. This analysis provides the first estimate of wet WtE resource prices. Our resource opportunity or

Weighted Project Score: 8.2

Weighting for Ongoing Projects: Approach - 25%; Accomplishments and Progress - 25%; Relevance - 25%; Future Work - 25%



"hot-spot" analysis indicates that high and very high potential is present in many states and follows population dynamics where fuel consumption is also high. Preliminary results for the cost-benefit analysis of food waste indicate that for a pathway to break even, it requires: (1) a tipping fee, (2) a facility of particular scale (larger facilities are able to offset their costs easier), and to a lesser extent depends on the value of products. Geographic variances in pathways stem from differences in tipping fees, fuel energy prices, and local wages. Project challenges include data availability and quality, which were mitigated by ongoing industry input.

OVERALL IMPRESSIONS

- As with the corresponding PNNL-based project (2.1.0.113), this project is performing an exhaustive yet essential task in collecting and organizing wet-waste feedstock quantity, location, and cost data down to a regional level. These data are critical in the development of corresponding waste-conversion technologies and the ability to determine where and how the overall cost of biofuel can be minimized by taking advantage of available low-cost wet wastes as feedstocks. The work in this project complements the work being done on the analogous PNNL-based project. The development of resource supply curves and cost-benefit analyses for various wet-waste feedstocks and conversion technologies is informative and the hot-spot analysis maps are particularly innovative. Starting a resource assessment study on MSW components is particularly encouraging in that it would represent a first attempt to characterize this large but underutilized feedstock. It would be helpful to see a specific list of tasks, milestones, and schedule for this project, which would allow one to get a better feel for whether the team has achieved its initial goals and whether there is sufficient time to complete the remaining work. Based on what information is provided, there does not appear to be sufficient time to complete the remaining work before the end of this project at the end of FY 2019. If this is the case, this project should be extended to at least complete the MSW component resource assessment.

- I do strongly believe that this type of project can provide the most significant contributions for the industry. These type of data sets are often inexistent or not widely available. The benefit provided to the industry by this analysis to the industry—an investigation that is difficult to carry out inside a private organization—cannot be overstated. The challenges that WtE has always had is competing with landfilling. Landfill margins are in general quite high, and when presented with the diversion to WtE, landfill operators have often been able to recapture those streams by undercutting the WtE solution to a point where WtE is no longer competitive. While landfill capacity remains high west of the Mississippi River, it is increasingly constrained east of it. Furthermore, changing dynamics in transportation costs are further limiting haulage of waste to distant landfills. It would be useful to overlay these maps to regional landfill locations, capacities, and trends and provide at least a qualitative direction on landfill disposition.

RECIPIENT RESPONSE TO REVIEWER COMMENTS

- We thank the reviewers for their comments and positive evaluation. Apologies for not including more information on milestones and schedule. The project is scheduled to continue through year 2020, which will allow us to complete all planned work.

- We thank the reviewers for their comments and positive evaluation. We certainly agree with the stated challenges that the WtE industry is facing and we will continue to work towards providing information in support of the industry's further development and decision making. We also agree with the reviewers' recommendation to analyze landfill locations, capacities, and trends; it is currently ongoing under the cost-benefit analysis task.

WTE: FEEDSTOCK EVALUATION AND BIOFUELS PRODUCTION POTENTIAL – PNNL

Pacific Northwest National Laboratory

PROJECT DESCRIPTION

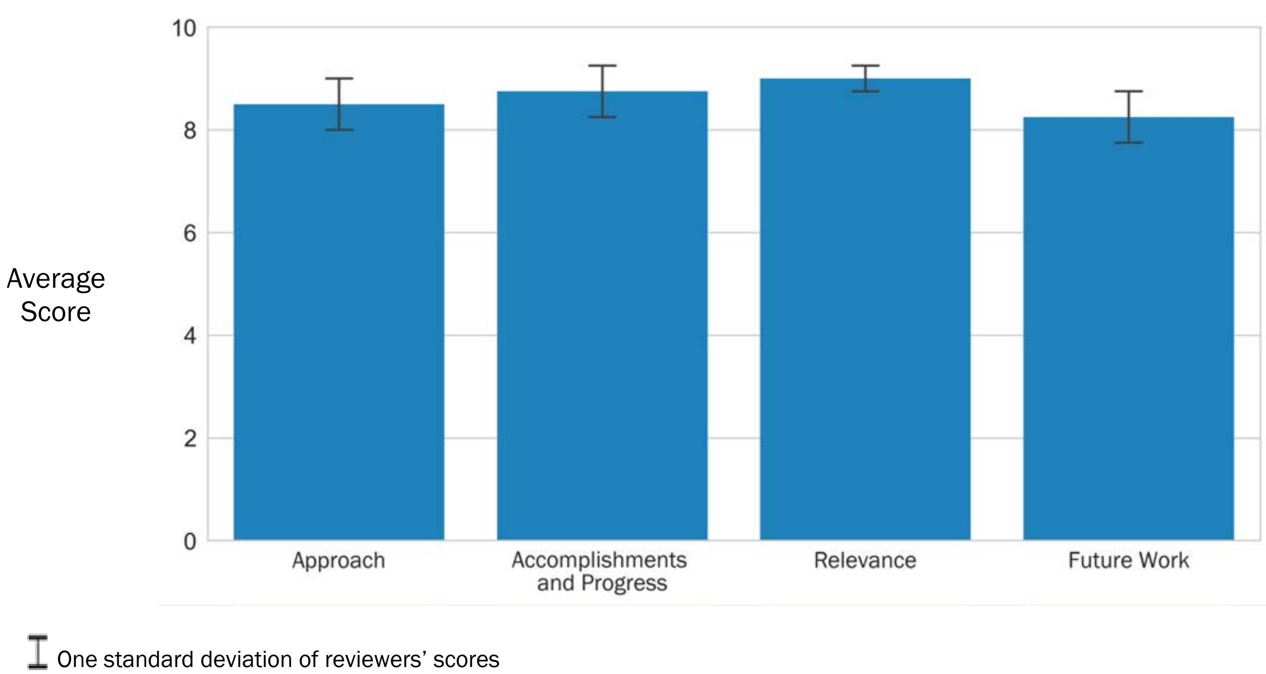
WBS:	2.1.0.113
CID:	NL0029527
Principal Investigator:	Dr. Timothy Seiple
Period of Performance:	10/1/2017–9/30/2020
Total DOE Funding:	$692,051
DOE Funding FY16:	$0
DOE Funding FY17:	$0
DOE Funding FY18:	$392,051
DOE Funding FY19:	$300,000
Project Status:	Ongoing

Waste is a liability, but it is also an underutilized source of carbon that could be diverted to renewable fuels and products. Which wastes offer the best value propositions (e.g., availability, existing collection infrastructure, ease of conversion, result in high-quality fuels)? What are the tradeoffs inherent to WtE enterprises? This project provides foundational data, modeling, and analyses to enable a nascent WtE industry to capitalize on the national, renewable stockpile of underutilized organic wet wastes.

The Biomass Assessment Tool (BAT), a high-resolution modeling platform developed with BETO support, was used to import site-specific waste resource data and pose WtE enterprise questions. Recent outcomes include assessment of wet WtE resources, estimated at approximately 76 million dry tons per year (MDT/yr), of wastewater sludge, animal manure, FOG, and food waste distributed among 56,000 sites. Using HTL as a proxy for thermochemical wet feedstock conversion, these wet wastes have annual average production potential of 5.6 billion diesel gallons equivalent.

Weighted Project Score: 8.6

Weighting for Ongoing Projects: Approach - 25%; Accomplishments and Progress - 25%; Relevance - 25%; Future Work - 25%



Current efforts include development of cost-benefit and feedstock blending analysis tools to (1) compare alternative wastewater solids treatment options to maximize energy recovery, minimize waste and disposal costs, and quantify cost-effective feedstocks; and (2) assess impacts of feedstock aggregation and blending on HTL biocrude yield, to provide "optimal" blending strategies based on biochemical composition for a given regional feedstock inventory. An illustrative finding from this work is that using 2017 solids treatment costs and 10-year average biofuel revenue conditions, HTL could economically utilize 11 MDT/yr of sludge, produce 1 billion diesel gallons equivalent, and reduce solids treatment and disposal costs by $1.5 billion per year from current practice.

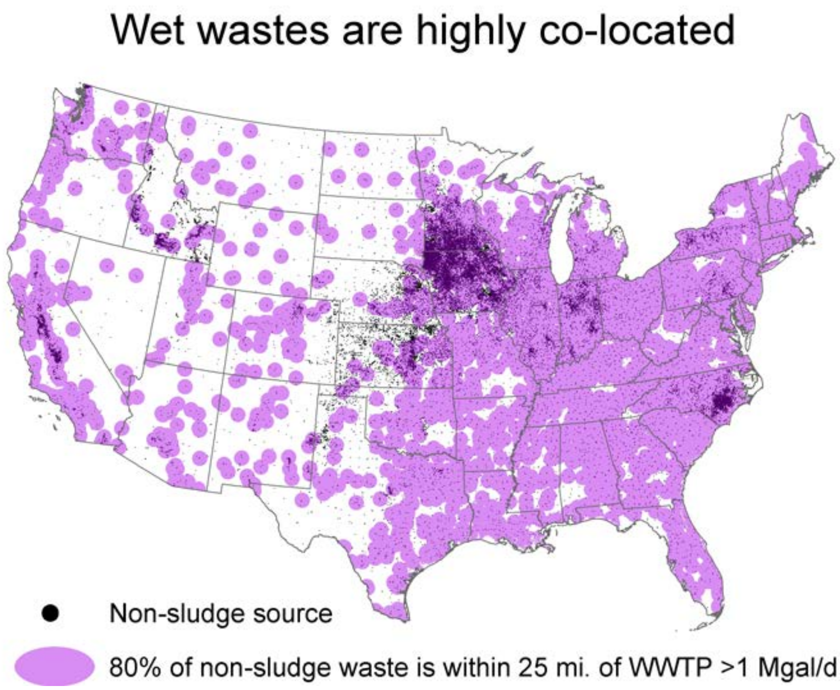


Photo courtesy of Pacific Northwest National Laboratory
Note: WWTP = waste water treatment plant, Mgal/d = million gallons per day

OVERALL IMPRESSIONS

- Because of the importance in understanding feedstock distribution and availability and because of the impact feedstocks have on the overall biofuel cost, the resource assessment work described in this project is critical to developing cost-effective biofuels. There is a tremendous amount of regional data that have to be uncovered, sorted, and processed in a project like this, so it is impressive to see what has been accomplished so far for wastewater solids as a feedstock. The insight gained on HTL economic feasibility and the economic comparison of HTL to AD are very valuable and show the considerable advantages that HTL has for handling sludge and for the wastewater utility industry, also justifying further development to commercial scale. Blending study results are consistent with those obtained by the HTL experimental and TEA teams but provide additional insight into what feedstocks are available and how blending might be accomplished on a regional level. It would be helpful to see a specific list of tasks and milestones for the remaining duration of this project so that it will be clear exactly what activities will be performed under the given broad topics (e.g., characterizing manure feedstock) and when they will be finished. There are so many directions in which one can go with the feedstock data developed in this project that there needs to be a clear, agreed-upon path forward.

- The systemic modeling exercise has intrinsic value, as they provide unique insight into a problem even when the final and actual solution may differ than what the model predicted. The comparison between HTL and AD is particularly insightful as it identifies a strong justification for the continued development of the technology. Internal economics (e.g., transportation) are not fully developed or at least explained in the presentation. Lastly, I would desire to see an effort in identifying possible externalities that may impact the system. For instance, an AD system in confined animal feeding operations provides a variety of ecological or environmental services, which are the main reason for their deployment. Examples of ecological or environmental services include odor control, nutrient management, water management, and solid recycling, with energy recovery being a desirable cost offset but not in most cases the primary driver. It essential that a way to assess these values and to ensure that they are maintained is considered in future work within this project or any possible follow up. The project is nonetheless a valuable contribution as it highlights and justifies, as already mentioned, continued work into the emerging HTL technology.

RECIPIENT RESPONSE TO REVIEWER COMMENTS

- We thank the reviewers for their time and critical review.
- To summarize the overall project, and context for current work, we previously focused on assessing feedstock quality and quantity for priority wet-waste sources, including sludge, manure, food waste, and FOG. Next, we assessed economically sustainable sludge feedstocks, blending potential and blend optimization. We are now quantifying economically sustainable manure feedstock sources and magnitudes and estimating the minimum feasible deployment scale of standalone on-farm HTL, with comparison to AD. These activities are all a precursor for a comprehensive economic, optimized blending and biorefinery integration assessment. The following milestones are defined for the remainder of the project:
    - Characterize manure systems for manure source terms (March 31, 2019; complete)
    - Develop a national-scale cost model (June 30, 2019)
    - Quantify sustainable manure sources, magnitudes, and scale (September 30, 2019)
    - Assess feasible waste aggregation, blending, and biorefinery integration (September 30, 2020).
- We agree that many internal economic assumptions are encapsulated in the data and models. A lot of work went into retaining spatial, temporal, and operational realism at the site, regional, and national scales. Our complete methodology and results will be in a peer-reviewed journal publication with downloadable detailed supplemental material.
- We will consider different strategies for waste aggregation for blending, by transporting either raw material, bio-oil, or a mix of both, depending on scale. We will model transportation logistics in the next phase to develop more realistic service areas.
- We agree with the reviewers that the externalities associated with WtE projects should be considered. As a follow-on, we have submitted a multi-lab proposal to develop a triple bottom line accounting framework to capture the value of ecosystem services provided by WtE technologies such as HTL.

ANALYSIS AND SUSTAINABILITY INTERFACE

Pacific Northwest National Laboratory

PROJECT DESCRIPTION

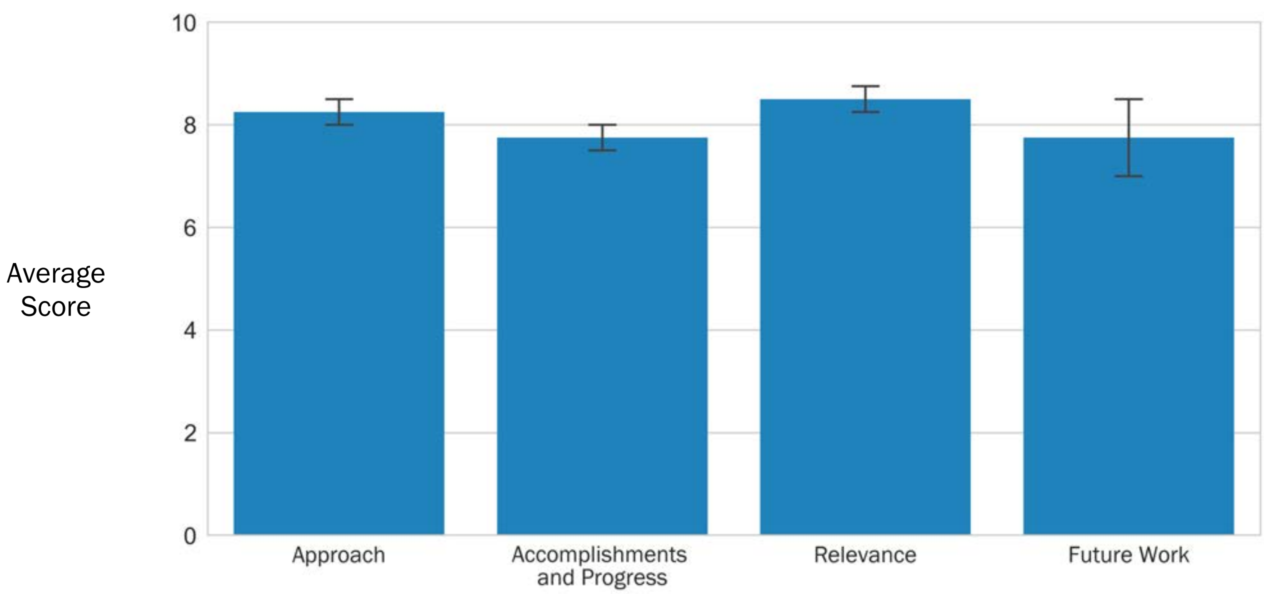
WBS:	2.1.0.301
CID:	NL0019451
Principal Investigator:	Ms. Sue Jones
Period of Performance:	10/1/2016–10/1/2019
Total DOE Funding:	$3,052,813
DOE Funding FY16:	$875,000
DOE Funding FY17:	$925,000
DOE Funding FY18:	$727,813
DOE Funding FY19:	$525,000
Project Status:	Ongoing

This project provides TEA and LCA for biomass conversion routes to hydrocarbon fuels and chemicals in order to direct research towards high-impact results. Targeted conceptual biorefinery models are developed with researcher input and compared against benchmark models that incorporate currently achieved research results. This (1) identifies barriers, cost-reduction strategies, and sustainability impacts; (2) helps set technical and costs targets; and (3) tracks research progress.

While this project provides analysis support in several biomass conversion research areas, the focus of this presentation is on TEA support for the wet-waste HTL and biocrude upgrading pathway. Building on extensive work with wood and algal feedstocks, HTL testing of municipal wastewater treatment plant sludges shows promising results in terms of fuel yields and quality. An added advantage is that this waste stream is a zero-cost, reactor-ready feedstock that is currently available and requires little preprocessing. The technology has garnered much interest from industry as an attractive future solution to current sludge management and disposal challenges.

Weighted Project Score: 8.1

Weighting for Ongoing Projects: Approach - 25%; Accomplishments and Progress - 25%; Relevance - 25%; Future Work - 25%



One standard deviation of reviewers' scores

A goal case design projecting research targets achievable by 2022 for the HTL and biocrude upgrading pathway was published in 2017, and the first SOT assessment was developed in FY 2018 to baseline progress to date and guide research and track advancement toward the goal. A key aspect to success is the continual integration of the experimental and analysis team's effort to define and target the research that will most significantly reduce cost while meeting sustainability goals. Research areas identified from this effort that are needed to achieve the target minimum fuel selling price include improved upgrading throughput rates and catalyst life, improved efficiency (reduced capital) for the HTL heat exchangers, and increased sludge feed solids content and biocrude yields.

In addition to the wet-waste HTL task, another specific key outcome of this project was the support for meeting the 2017 BETO goal, "by 2017, validate an n^{th} plant modeled minimum fuel selling price of \$3/GGE (2014\$) through a conversion pathway to hydrocarbon biofuel with greenhouse gas emissions reduction of 50% or more compared to petroleum-derived fuel." This was met by working closely with LanzaTech and the PNNL team, who developed and demonstrated the technology to convert syngas to fuels and chemicals. Idaho National Laboratory (INL) provided feedstock costs and a life cycle inventory was provided to ANL for the greenhouse gas emissions calculations. In a similar way, the wet-waste HTL analysis task is directed towards meeting BETO's 2022 cost-reduction goals for fuel production.

Data availability is a common challenge for all analysis projects. This is mitigated by frequent, close interactions with researchers to exchange information and review sustainable cost-reduction strategies. Collaboration with analysts at ANL, INL, NREL, and Oak Ridge National Laboratory (ORNL) enhance project effectiveness. Frequent communication with BETO technology leads ensures impactful outcomes. Disseminating results for use by stakeholders is achieved through publications and presentations.

Photo courtesy of Pacific Northwest National Laboratory

OVERALL IMPRESSIONS

- This project demonstrates the value and importance of incorporating TEA modeling with experimental research work. The work in this project complements the PNNL HTL experimental work on wet wastes nicely and provides a pathway to identify the parameters that may have the biggest impact on overall biofuel cost and therefore justify further research attention. While predicted results do not always match reality, the approach described and being implemented in this project to verify and inform research is likely the most efficient way to converge on the BETO overall biofuel cost target of $3/GGE. The preparation of yearly SOTs starting in 2018 will provide a yearly benchmark to assess how close the team is to achieving the BETO target. This project, which is scheduled to end at the end of FY 2019, has clearly demonstrated its value and deserves to be continued.

- Overall, I like the project and the modeling framework presented is undoubtedly of value and worth further development. However, it may be overambitious for the time left, and while the important insight on cost reduction of hydrotreating is very valuable, it should be further developed in detail.

- Overall a really good project, providing insight into the economic trajectory necessary for HTL of wet waste to be an economically successful fuel.

RECIPIENT RESPONSE TO REVIEWER COMMENTS

- We very much appreciate the reviewers' time and efforts in providing critical evaluation and valuable feedback for this project.

- We may have inadvertently communicated in the "Future Work" slide that the wet-waste HTL task within the project is ending this year along with other parts of the project. However, the intent is to propose that this work continue in a new three-year project to focus on this pathway through FY 2022, when the technical and cost goals for the pathway are expected to be met.

- While it was difficult with the time allotted to present the details of the models, a table of primary inputs and assumptions could have been presented to provide the reviewers more background. In addition, the design case and other publications will be referenced for providing the details of the model.

- The lifecycle carbon intensity is evaluated for each pathway and integrated into the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model. Revenue streams from renewable fuel program credits are not included in BETO pathway TEAs in order to avoid overestimating the future economic potential when such programs may not exist. However, the need to include biofuel credits in the economics was echoed by several in the audience who feel it is unfair to ignore this potential revenue stream, and somewhat counterproductive because these programs are specifically intended to help foster new technology commercialization.

- The missing feedstock cost category has been brought up by our industry partners and perhaps deserves revisiting based on the reviewer's comment. A possible way to manage this in future work is to present an additional graph of feedstock cost versus minimum fuel selling price in the BETO Multi-Year Plan, to represent the avoided cost that would be incurred by a wastewater treatment plant today, as well as the variability that exists.

- We are currently investigating methods and associated costs for removal and recovery of nutrients from the waste streams, including ammonia nitrogen from the HTL aqueous phase and phosphorus from the HTL ash/solids.

BENCH-SCALE HTL OF WET-WASTE FEEDSTOCKS

Pacific Northwest National Laboratory

PROJECT DESCRIPTION

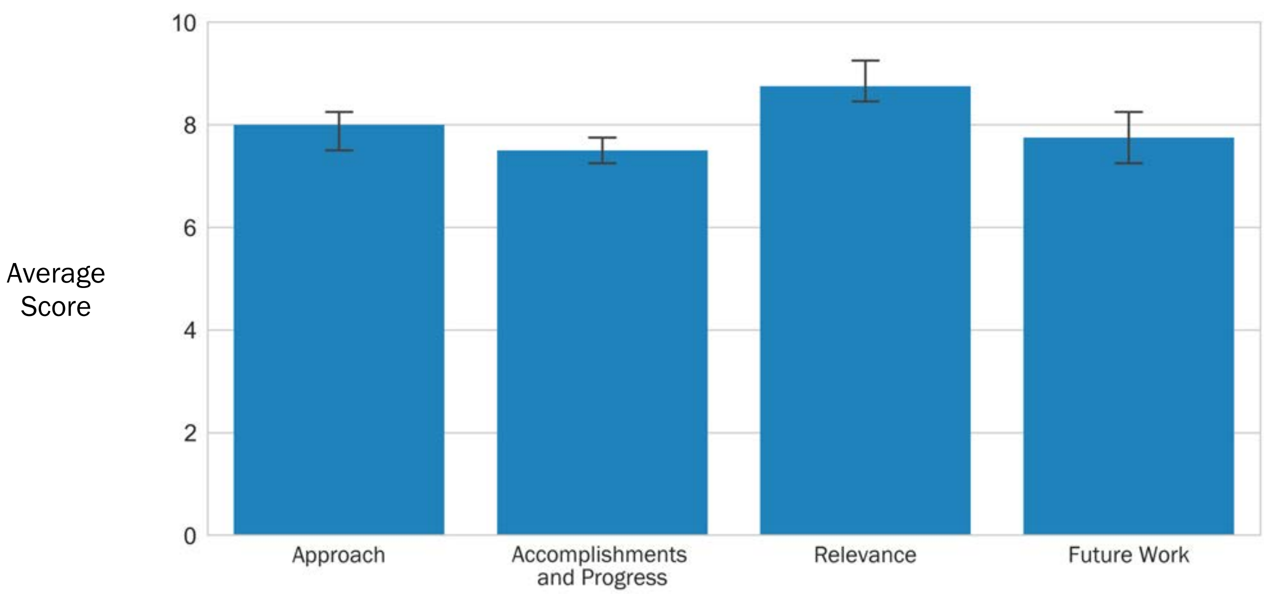
WBS:	2.2.2.302
CID:	NL0034882
Principal Investigator:	Mr. Justin Billing
Period of Performance:	10/1/2018–9/30/2021
Total DOE Funding:	$360,000
DOE Funding FY16:	$0
DOE Funding FY17:	$0
DOE Funding FY18:	$0
DOE Funding FY19:	$360,000
Project Status:	Ongoing

Waste is a liability, but it is also an underutilized source of carbon that could be diverted to renewable fuels and products. Sewage sludges and manures are high-moisture, high-ash feedstocks that benefit from robust wet-processing technologies such as HTL. Early-stage R&D is essential for understanding wet feedstock performance and blended feedstock behavior, as well as options for aqueous-phase treatment and/or recycling.

PNNL has adapted HTL operations and cultivated relationships with industrial partners needed to advance the HTL pathway for wet-waste feedstocks, resulting in reduced overall conversion cost, improved sustainability, and decreased technological risks for industrial partners in support of BETO's mission to reduce technological costs and risks. Experiments are designed to develop foundational understanding of HTL conversion to biocrude, catalytic biocrude upgrading, and aqueous-phase treatment technologies, and to generate data packages for the Analysis and Sustainability project, which reports the annual SOT for the HTL of the sewage sludge pathway. In turn, future research is identified and prioritized from SOT modeling and TEA such that areas of greatest impact and highest technical risk are addressed first.

Weighted Project Score: 8.0

Weighting for Ongoing Projects: Approach - 25%; Accomplishments and Progress - 25%; Relevance - 25%; Future Work - 25%



One standard deviation of reviewers' scores

Feedstock selection is guided by the WtE resource assessment project, a PNNL and NREL collaboration. Geospatial representation of feedstock availability highlights sites and regions where resources may support the scale of operations required for commercialization. Testing selected feedstocks at the bench scale provides valuable feedback on the biofuel production potential of a given resource and refines the assumptions of the resource assessment. Bench-scale testing also helps screen and qualify feedstocks for the Hydrothermal Process Development Units project.

Recent findings indicate that yields up to 45% of energy-dense biocrude can be produced from sewage sludge with significant ash content (up to 30%). Streams of underutilized FOG such as wastewater scum can be blended into sewage sludge to boost yields even more. Much of the technology development on algal feedstocks has been found to apply to wet-waste feedstocks, including strategies for catalytic upgrading of the biocrude. If low-cost wet-waste feedstocks perform as well on the HTL platform, there is a real opportunity for scale-up and deployment.

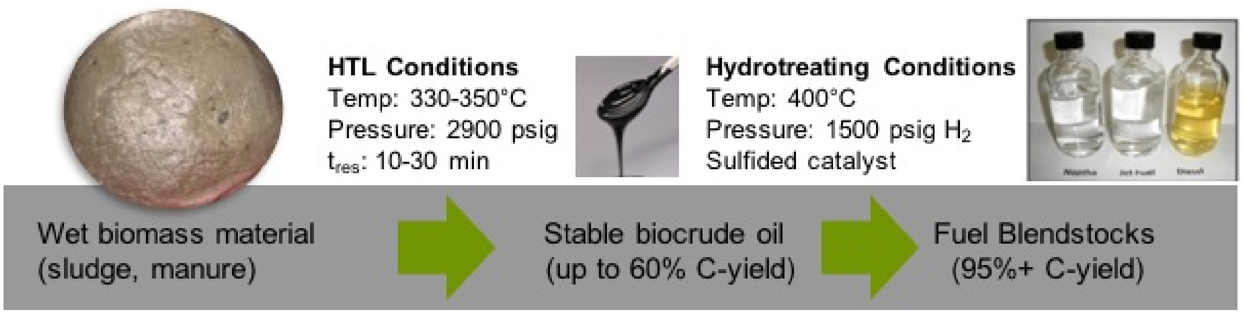


Photo courtesy of Pacific Northwest National Laboratory

OVERALL IMPRESSIONS

- This project, which utilizes a wet-waste feedstock for conversion to liquid biofuels through HTL, represents an ideal pathway for meeting many of BETO's most significant goals. In trying to achieve the elusive $3/GGE biofuel cost target, the use of waste feedstocks eliminates the feed cost (or creates an even better situation with a negative cost) from the overall fuel cost. The use of HTL technology eliminates the relatively expensive costs to dry and extract particular components from the feed. The close coupling of experimental and modeling work as demonstrated in this project is critical to helping target research on parameters and threshold values most critical to the overall cost. As a whole, this project represents a methodical, efficient approach to reducing the remaining production costs as they strive to reach the BETO target. The fact that there are plans for the construction and demonstration of two HTL pilot-scale systems outside of this project further demonstrates the level of maturity and interest by external customers. While there were relatively limited test data reported at the current time, the project as currently defined has only been in existence for about five months and has a total duration of only one year. Because the mechanism and management appear to be set in place for significant advancements in HTL technology, the project duration should be extended to allow several research/modeling cycles to occur to see if the results live up to the potential.

- HTL has several exciting characteristics, as it can handle wet or watery streams and provide a liquid feedstock suitable for direct hydrotreating into fuel or a fuel blendstock. While the integration of all the various components is not trivial, HTL is undoubtedly better suited to WtE than fast pyrolysis. While still in its infancy compared to AD, HTL has potential benefits that justify this effort. Work at the bench scale with a variety of feedstocks is critical. Experimentally, this work appears to be quite good. I see several weaknesses in the analysis part, especially as it pertains to the impact to the TEA and the boundary interaction with other technologies, such as hydrotreating, which could be used to directly treat some of the feedstocks (e.g., FOG) identified as a blendstock. Some of the numbers are a bit overoptimistic in real life, while technically correct (e.g., carbon fuel yield). Is the use of HTL bio-oils directly as fuel for combined heat and power feasible?

- As a non-engineer or chemist, I appreciate the introduction to HTL.

RECIPIENT RESPONSE TO REVIEWER COMMENTS

- We thank the reviewers for a thorough evaluation of the HTL technology as applied to wet-waste feedstocks and plan to propose continuing research in accordance with the recommendation to extend the project duration.

- The HTL team thanks the reviewer for recognition of the importance of continued bench-scale research and for correctly assessing the opportunity available for the conversion of wet waste. Using wastewater treatment plant scum (FOG) as a feedstock blend is one option to increase yield but scum addition is not integral to the process and will be responsive to the site-specific market conditions. HTL biocrude could likely be combusted or co-combusted for combined heat and power but our project focus is aligned with the BETO goal of advanced liquid transportation fuels from wet-waste feedstocks.

- We are thankful for the question about combined heat and power, as this question comes up frequently in discussion with wastewater treatment plant operators whose primary interest is sludge disposal and secondary interest is heat, electricity, or natural gas for reuse onsite, or renewable natural gas credits in the case of natural gas. The small and distributed nature of wet-waste resources might drive pioneering projects to consider routes besides catalytic upgrading because downscaling a standalone hydrotreater is not economical and the path to refinery coprocessing may not be established. In time, increasing regional production of HTL biocrude may support a standalone hydrotreating unit and/or the path to coprocessing will be better defined.

- We appreciate the time and effort required of the reviewer to learn and evaluate WtE technologies such as HTL.

ARRESTED METHANOGENESIS FOR VOLATILE FATTY ACID PRODUCTION

Argonne National Laboratory

PROJECT DESCRIPTION

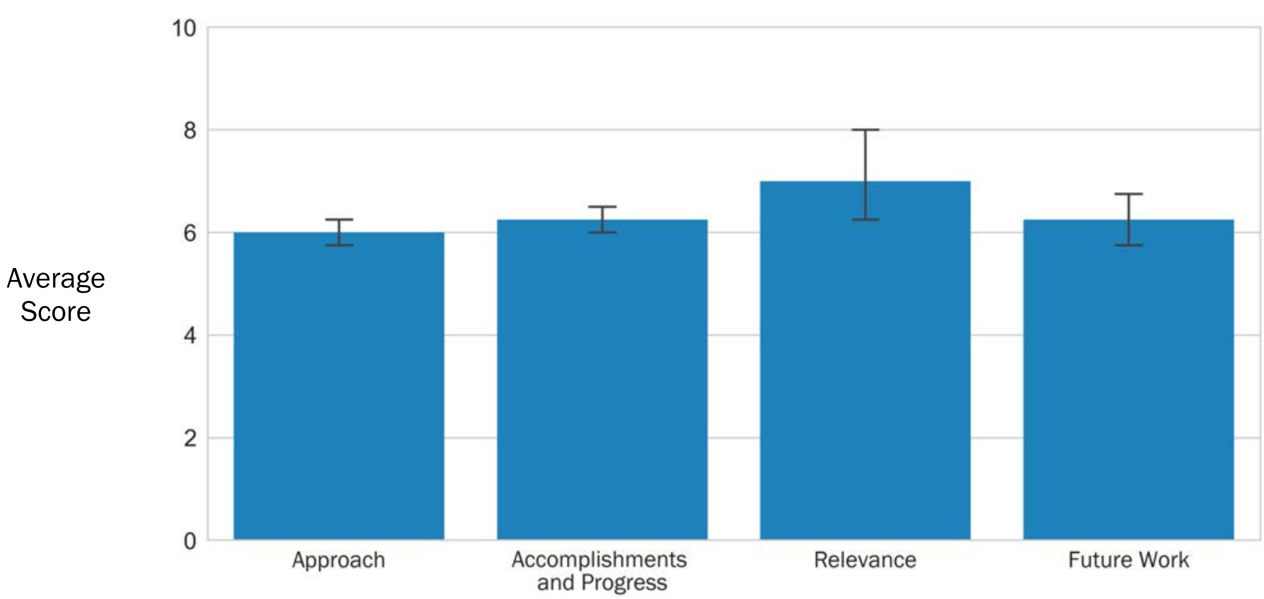
WBS:	2.2.4.100
CID:	NL0026648
Principal Investigator:	Dr. Meltem Urgun-Demirtas
Period of Performance:	10/1/2015–9/30/2020
Total DOE Funding:	$2,300,000
DOE Funding FY16:	$750,000
DOE Funding FY17:	$550,000
DOE Funding FY18:	$500,000
DOE Funding FY19:	$500,000
Project Status:	Ongoing

This project supports BETO's mission to develop new technologies that produce biofuels and products from nonfood U.S. feedstock resources such as agricultural residues and wet waste (e.g., food waste). We rewire the dark fermentation process to produce short-chain organic acids through arrested methanogenesis. The proposed technology has the potential to make a substantial contribution to BETO's advanced biofuel pathway portfolio.

The project objectives are to (1) define concepts and develop tools to transform low-value or negative-value high-strength organic waste streams into high-value short-chain organic acids (C2–C6); (2) rewire the dark fermentation process to produce organic acids via arrested methanogenesis sustainably; (3) regulate acidogenic metabolism toward enhanced organic acid production; (4) establish highly efficient, robust, and productive community structures for organic acid production; and (5) develop new arrested AD technologies (a.k.a. the carboxylate platform). Our ultimate goal is to develop new AD technologies from a proof of concept, TRL 2 to TRL 4 at the end of three years of project duration to produce organic acids continuously at a titer of 12.5 g/L

Weighted Project Score: 6.4

Weighting for Ongoing Projects: Approach - 25%; Accomplishments and Progress - 25%; Relevance - 25%; Future Work - 25%



One standard deviation of reviewers' scores

in 200-gallon digesters. We have been developing a new high-rate arrested AD process for transforming organic waste by supplanting starch, sucrose, or glucose currently used as feedstock into organic acids. We design and construct an anaerobic membrane bioreactor technology to produce and separate organic acids from the fermenters to facilitate high product yield, minimize the toxicity of organic acids, reduce mass transfer limitations, and ensure the health, stability, and productivity of AD communities.

This research specifically determines the links between organic wastewater characteristics, microbe community structure, and the design and operation of high-rate arrested AD system at the bench scale. Specific research targets include the isolation and integration of highly diverse microbial functionalities within high-rate arrested AD fermenters for high-strength organic wastewater treatment coupled to renewable chemical production. We started with wastewater streams generated at dairies and breweries as initial carbon sources because of their high carbon content and biodegradability.

The outcome of this project is a new cost-effective AD technology at TRL 4 at the end of the project. Additionally, this technology is appealing because it has the potential to produce high-value chemicals without competing either directly or indirectly with food or animal feed production.

OVERALL IMPRESSIONS

- This project is one of several looking at arrested AD in which the conventional AD process mechanism is stopped at the VFA production step rather than going on to produce methane. Thus, the focus is on producing intermediate chemical products rather than biogas, which generally results in a product of greater value. The concept is a good one and this project has generated quite a bit of good data on microbial consortia that will deliver the VFA concentrations near target levels under a variety of operating conditions and feedstocks at the bench-scale level, even though it is not entirely clear how the methanogenesis step is being shut down. As a result, the project has proven the arrested AD concept for generating VFAs, at least during short-term operation. Data on separation of VFA products are not as encouraging at the present time, and it is not clear what methods will be further investigated and/or used in larger-scale systems. Without knowing what the actual market value of the low-carbon VFA species being generated is (relative to the base case of biogas generation), difficulty in isolating the desired product(s) may result in a process that is not economically viable. An additional concern with this project is that two scale-ups will need to be performed and demonstrated in the remaining year and a half of the project duration, which may be difficult to achieve even with an industrial partner on board.

- This is one of several projects looking at arrested AD to produce higher-value products. I think the choice of reactor configuration may limit its relevance if scaled up to low dissolved solids streams, a relatively smaller subset of wet wastes. Furthermore, ion exchange resin for organic acid separation is an expensive approach for a mixed stream of chemical commodities. The economic value is only in a small subset of organic acids, and the lack of TEA makes it difficult to evaluate its relevance.

RECIPIENT RESPONSE TO REVIEWER COMMENTS

- Methanogenesis was inhibited by following different methods: acid and heat treatment of inoculum, increasing organic loading rate and reducing hydraulic and sludge retention times, as well as running the digesters at pH ≤ 6.0 instead of an optimum pH range of 6.5–7.5. Increasing the loading rate and reducing the retention time was done to washout any slow-growing, methane-producing bacteria and archaea. Additionally, high concentrations of organic acids and salts inhibit the growth of methanogens in the digester environment. Please see the presentation for more information.

- For the separation of acids from the fermenter broth, ion exchange resins and membranes are currently being used at industrial-scale applications. Resins and membranes were purchased from the manufacturers (e.g., Dow and GE). The scalability of the tested separation technologies is not an issue because they're currently at the field scale. For example, reverse-osmosis membranes are used for recovery of acetic acid from the petrochemical plants and food production plants.

- Our project is guided by the outcomes of TEA conducted by NREL (PI: Tao; 2.1.0.111) The TEA is used to synergize research from waste collection and handling to VFA production, purification, and utilization (e.g., platform chemicals). The project team will provide results of the detailed process modeling and simulation efforts to NREL. NREL's integrated approach will project cost potentials and research targets from an overall economic point of view. This is to determine titer, yield, productivity, and recovery targets necessary to produce an economically viable organic acid production for various applications and uses. In order to answer critical questions such as "At what R&D level would the proposed technology make economic sense?" we will perform sensitivity analyses and provide contour plots of economics for key matrices or cost drivers. We will outline barriers, highlight R&D needs for conversion and separation strategies, and provide critical inputs to successfully approach $2/GGE. These key findings will then be informed to the R&D team and BETO.
- AD and membrane-based technologies are very well known and can be easily scaled up from bench to pilot scale. The project team believes that three years of project duration would be sufficient to scale up the modular AD technology.
- As described in the presentation, two different reactor configurations specifically sequencing batch anaerobic reactor and anaerobic membrane reactor have been developed. This was done due to waste-stream characteristics and application points and sizes of the new AD at the utilities and facilities.
- We partially agreed with the reviewer's comment. Ion exchange resins were purchased from commercial resin manufacturers. These resins have been used for organic acid separation at field scale. TEA of organic acids is also a part of NREL's project (2.1.0.111).

BIOGAS-TO-LIQUID FUELS AND CHEMICALS USING A METHANOTROPHIC MICROORGANISM

National Renewable Energy Laboratory

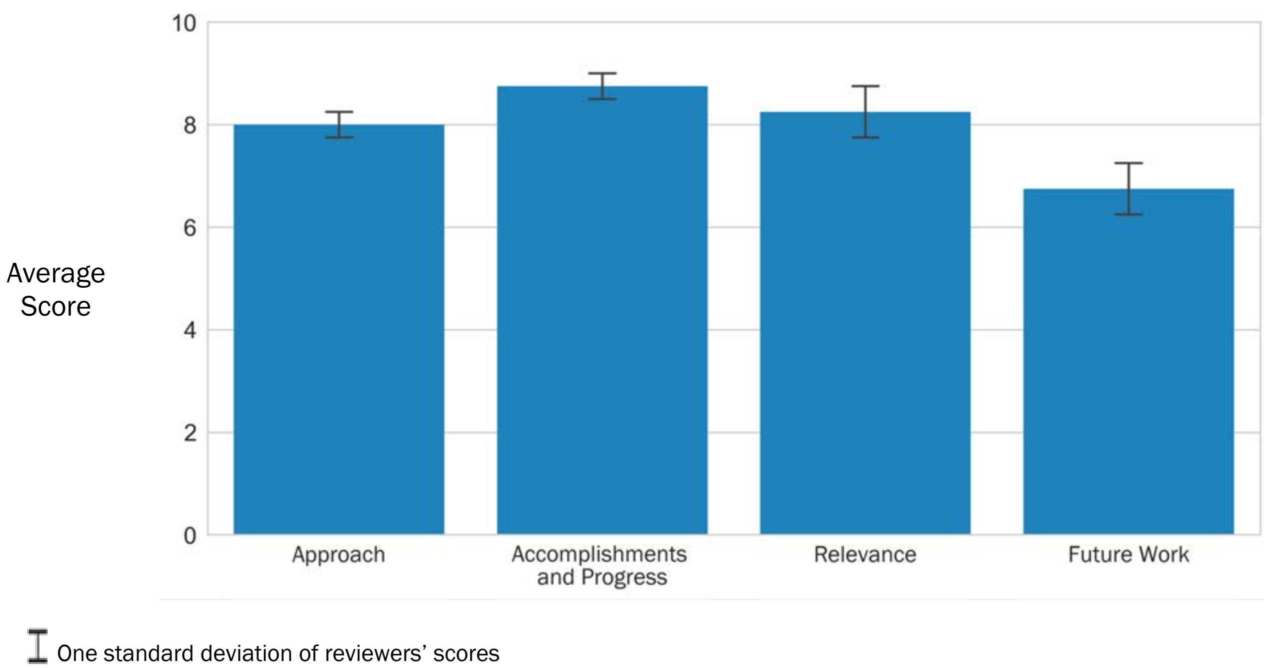
PROJECT DESCRIPTION

WBS:	2.3.2.102
CID:	NL0026680
Principal Investigator:	Dr. Mike Guarnieri
Period of Performance:	10/1/2015–9/30/2021
Total DOE Funding:	$1,515,008
DOE Funding FY16:	$250,000
DOE Funding FY17:	$400,000
DOE Funding FY18:	$465,008
DOE Funding FY19:	$400,000
Project Status:	Ongoing

Biogas derived from anaerobic digestion of waste streams such as biorefinery wastewater, animal, agricultural, and MSW offers a versatile renewable energy source. Total domestic methane potential from landfill material, animal manure, wastewater, and organic waste is estimated to be greater than 4 quadrillion British thermal units (Btu). Additionally, biogas generated from AD of lignocellulosic biomass resources is estimated to offer 4 quadrillion Btu potential energy. This energy potential could displace nearly half of current domestic natural gas consumption in the electric power sector and all current natural gas consumption in the transportation sector. However, despite the promise of biogas as a high-volume, renewable energy source and natural gas replacement, its gaseous state prevents facile integration with extant transportation and industrial infrastructure. At present, biogas is primarily flared or used to produce combined heat and power. Alternatively, AD biogas can be scrubbed for conversion to biomethane that can, in turn, be utilized as a renewable option in natural gas applications.

Weighted Project Score: 7.9

Weighting for Ongoing Projects: Approach - 25%; Accomplishments and Progress - 25%; Relevance - 25%; Future Work - 25%



Microbial conversion of biogas to liquid fuel and chemical intermediates using natural methane-consuming bacteria (methanotrophs) offers valorization potential. However, biogas biocatalysis is currently limited by low conversion efficiencies and incomplete biogas utilization. The development of a biocatalyst capable of high-efficiency co-utilization and conversion of methane (CH_4) and CO_2 would allow for complete utilization of biogas streams, significantly improving process economics and enhancing carbon conversion efficiency to target products. Additionally, development of a CH_4/CO_2 co-utilizing biocatalyst would dramatically shift the landscape of carbon capture and conversion pursuits, providing a novel, photosynthesis-independent CO_2 biocatalyst.

The Biogas Biocatalysis annual operating plan aims to develop a carbon- and energy-efficient biogas bioconversion process via rational, techno-economic-informed strain and fermentation engineering strategies. Specifically, we will evaluate mechanisms of CH_4 and CO_2 utilization in phylogenetically diverse methanotrophs and leverage those learnings to develop an industrially relevant biocatalyst capable of CH_4 and CO_2 co-utilization. Concurrently, this project targets the development of methanotrophic biocatalysts with broad product suite capacity through rational metabolic engineering and adaptive laboratory evolution strategies. The resultant methanotrophic biocatalysts will provide a direct path to improve process economics and efficiency of lignocellulosic biorefineries and standalone AD infrastructure.

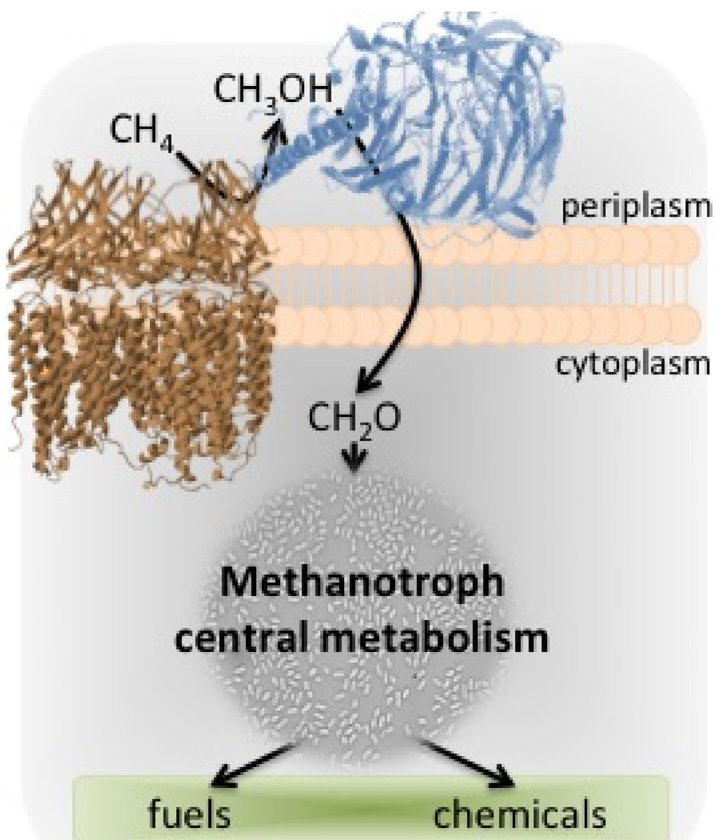


Photo courtesy of National Renewable Energy Laboratory

OVERALL IMPRESSIONS

- This project looks to improve on conventional AD in two ways: (1) by converting relatively low-value biogas to higher-value liquid chemical products (e.g., organic acids) and (2) co-utilizing CH_4 and CO_2 in the biogas conversion to liquid products, thereby increasing the carbon efficiency. These improvements all revolve around genetic engineering of methanotrophs, guided by TEA modeling, to achieve the target goals. The results so far have been impressive, with significant achievements made in organic acid product titer, rate, and yield and in modified microbes with enhanced CO_2 uptake capabilities. The collaboration among academia and industry stakeholders is also encouraging. Although future work has not been as clearly articulated as it could be, continued research on improving methanotroph strains to produce higher chemical product yields while utilizing more of the total carbon in the biogas, along with continued informed guidance from TEA modeling and sensitivity analysis, will help further enhance the viability of this work.

- In the last several years, we have seen increased interest in the development of processes based on methanotrophic organisms given the abundance of inexpensive natural gas as a carbon source. Adding to that the ability to directly use CO_2 makes the work on methanotrophs of even higher relevance for biogas, as it both increases the carbon efficiency of the waste feedstock transformation and has other process benefits such as reducing the need for expensive biogas treatment or accepting a diluent in the feedstock stream. Gas fermentation remains intrinsically challenging and much work remains to be done before a viable pathway to commercialization can be demonstrated. Nonetheless this is work of great value as it tackles and provides insights on the fundamental issue of general industrial value.

RECIPIENT RESPONSE TO REVIEWER COMMENTS

- We thank the reviewers for their positive and encouraging feedback. As noted by the review panel, we feel the development and deployment of methanotrophic biocatalysts with complete biogas substrate utilization and broad biosynthetic capacity will have a significant impact upon the burgeoning methane bioconversion space, as well as a substantial impact on the BETO WtE platform.

- We agree with the reviewers' assertion that gas fermentation remains intrinsically challenging. Though gas fermentation reactor development is outside the scope of this project, it is our hope that the development of robust methanotrophic biocatalysts with maximal C1 carbon conversion capacity will minimize the technical barriers associated with the microbial component of gas fermentation. To this end, our metabolic engineering efforts have generated the most carbon-efficient methanotrophic biocatalyst reported to date, possessing CH_4/CO_2 co-utilization capacity.

- The development of enhanced methane biocatalysis strategies offers a means to expand BETO's feedstock portfolio and represents a significant commercial opportunity to deploy WtE technologies. Additionally, the methanotrophic bioconversion strategies under evaluation have the potential to enhance the economics and sustainability of lignocellulosic refining as a bolt-on technology. To this end, future efforts will explicitly target cost reductions and yield enhancements to lignocellulosic refining via coproduction of high-value coproducts derived from wastewater AD biogas. Continued metabolic engineering and TEA efforts to identify the performance metrics required to incur a net economic and life cycle benefit will be pursued. Additionally, fundamental research targeting enhanced CH_4/CO_2 co-utilization will continue to be a core focus of our work. Our team is excited to continue these efforts and looks forward to continued progress in the development of a viable biological biogas conversion platform.

SEPARATIONS IN SUPPORT OF ARRESTING ANAEROBIC DIGESTION

National Renewable Energy Laboratory

PROJECT DESCRIPTION

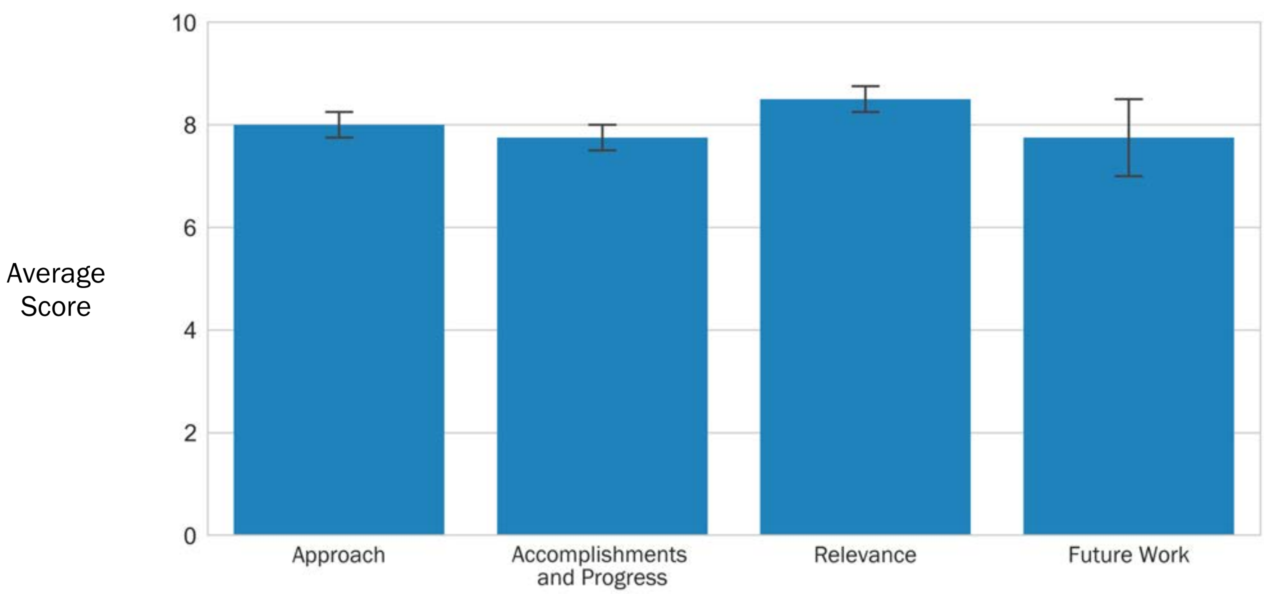
WBS:	2.3.2.107
CID:	NL0033407
Principal Investigator:	Dr. Eric Karp
Period of Performance:	10/1/2017–9/30/2020
Total DOE Funding:	$500,000
DOE Funding FY16:	$0
DOE Funding FY17:	$0
DOE Funding FY18:	$250,000
DOE Funding FY19:	$250,000
Project Status:	Ongoing

In support of BETO's interest in converting waste feedstocks to fuels and chemicals, this project aims to develop and demonstrate a system for the production of platform carboxylic acids by arresting AD of wet-waste feedstocks. The project addresses three key technology barriers in developing the bioeconomy, specifically (1) feedstock availability and cost, (2) selective separation of organic species, and (3) first-of-a-kind technology development. The project has been operational for 1.5 years of its planned 3-year timeline and is currently on track.

In the existing lignocellulosic biorefinery model, feedstocks typically account for 60%–70% of the produced biofuel cost. This feedstock cost can be overcome through the use of waste feedstocks that are cost advantaged or often cost negative (e.g., MSW, food waste). However, only recently have chemical products other than methane been the subject of R&D from the AD of waste. In an anaerobic digestor, a nonsterile microbial consortium converts waste through a series of four steps: (1) hydrolysis, (2) acidogenesis, (3) acetogenesis, and (4) methanogenesis. Each step occurs sequentially and is thermodynamically downhill in energy from the previous step. Accordingly, the process is driven continuously because the final methane product leaves the system as a gas.

Weighted Project Score: 8.0

Weighting for Ongoing Projects: Approach - 25%; Accomplishments and Progress - 25%; Relevance - 25%; Future Work - 25%



One standard deviation of reviewers' scores

This project aims to produce platform carboxylic acid chemicals by the *in situ* product recovery (ISPR) of VFAs that are produced during anaerobic digestion in step 2 above. To achieve this, work within this project is designing and building a first-of-a-kind ISPR system to recover neat VFAs as they are produced, and work focusing on the biological aspects of the AD unit are also undertaken to identify feedstocks, conditions, and cultures that are most appropriate to facilitate VFA production.

Key results from the project are that in order for the ISPR system to work, the AD unit must operate at a pH less than 5 and reach steady-state titers greater than 17 g/L. This places pressure on the culture to operate in low-pH environments. Results from serum bottle experiments and semicontinuous cultures have shown that a nonsterile culture can achieve these operational targets provided a readily digestible feedstock is used, as the hydrolysis step is the rate-limiting step in AD. Work is continuing to identify ideal feedstocks and cultures for these operational parameters and to integrate the ISPR system with a VFA-producing AD unit. Currently, the ISPR system has been demonstrated with mock cultures matching the VFA profiles measured from the semicontinuous culture and the AD unit has met the required operational targets. In the following 1.5 years of the project, the ISPR system is being adapted to handle higher solids content usually found in AD units and the AD unit will be integrated for a demonstration of *in situ* production purified VFAs.

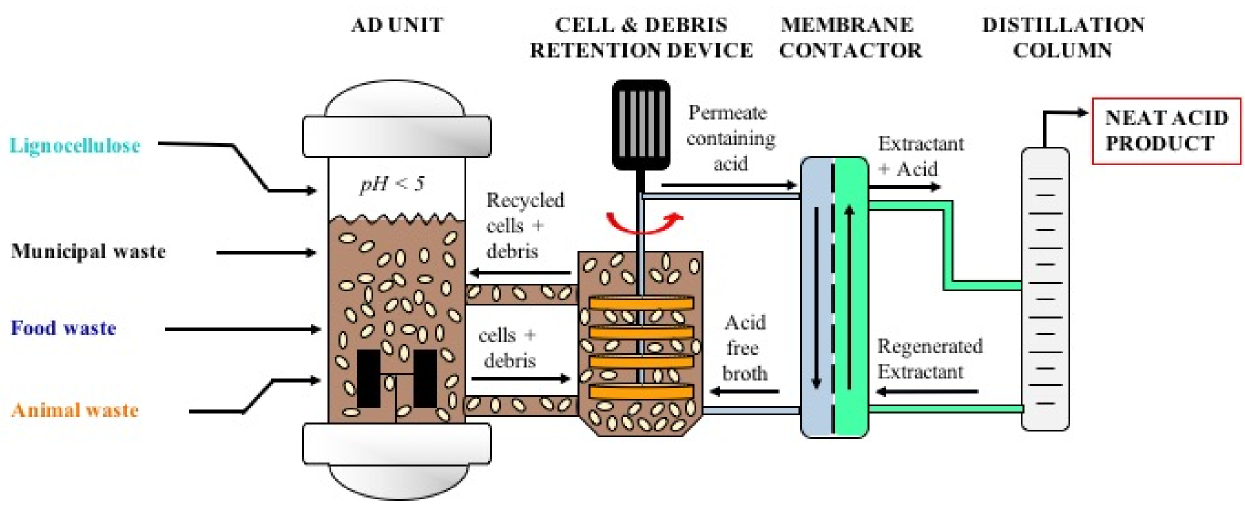


Photo courtesy of National Renewable Energy Laboratory

OVERALL IMPRESSIONS

- This is one of several projects focusing on the development of arrested AD for bioproduct generation instead of biogas. Splitting the project up into two parts (biology and separations technology) under separate control makes sense because these are the two areas where work is needed for this technology development. It appears that notable progress has been made so far on this project in terms of microbe culture choice for verifying the concept of VFA product generation, demonstrating 90% recovery of VFA products in a model of the proposed separations system and verification of flash drum behavior. The remaining work of completion of assembly of an integrated, functioning system that can meet predetermined VFA targets is reasonable and logical for assessing the full viability of the arrested AD concept. A critical demonstration will be to show long-term stable operation and a stable microbe community while being able to continuously remove VFAs before they can be transformed to methane. A discussion on the actual current market value of the low-carbon VFA species being targeted relative to the base case of biogas generation in conventional AD is not provided, but should be because it is important in assessing whether the cost of the arrested AD process being developed has a chance at being economically viable.

- Overall one of the more game-changing projects I saw in the review, due to the ISPR technology.

RECIPIENT RESPONSE TO REVIEWER COMMENTS

- The information on the TEA of this and other projects was presented separately in an analysis presentation following this presentation. That task is WBS 2.1.0.111.

REVERSING ENGINEERING ANAEROBIC DIGESTION OF WET WASTE FOR BIOFUELS INTERMEDIATES AND BIOPRODUCTS

National Renewable Energy Laboratory

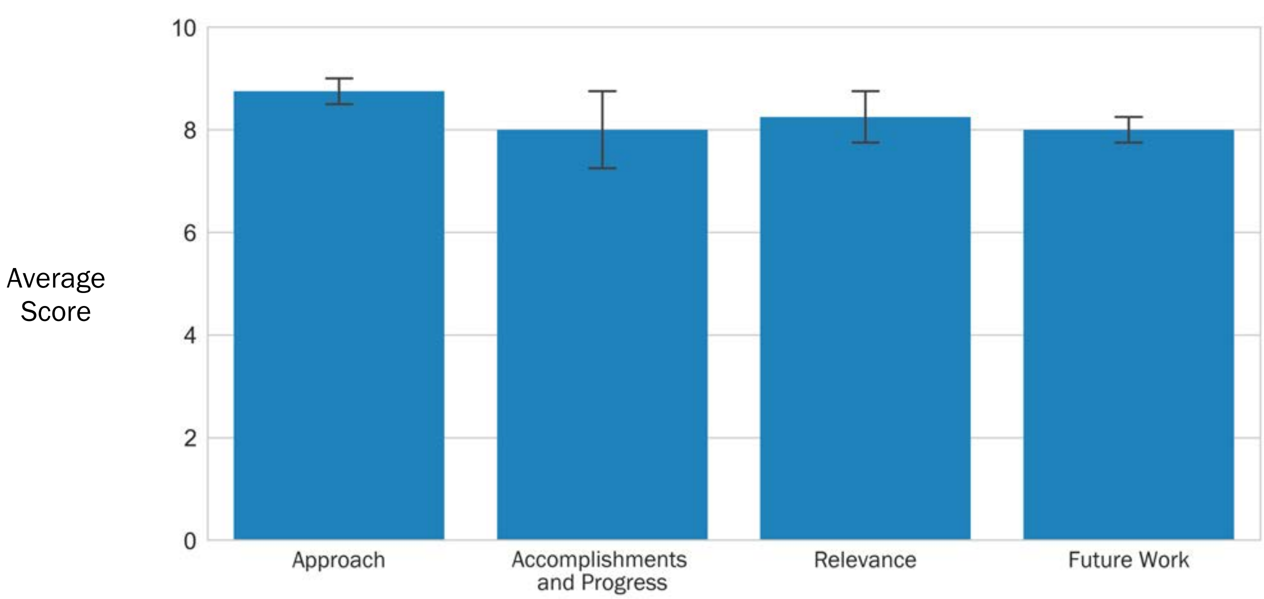
PROJECT DESCRIPTION

WBS:	2.3.2.108
CID:	NL0033408
Principal Investigator:	Dr. Steve Decker
Period of Performance:	10/1/2017–9/30/2020
Total DOE Funding:	$1,000,000
DOE Funding FY16:	$0
DOE Funding FY17:	$0
DOE Funding FY18:	$500,000
DOE Funding FY19:	$500,000
Project Status:	Ongoing

The project addresses BETO's increasing interest in conversion of wet waste to fuels and chemicals through anaerobic digestion by targeting increased hydrolysis of lignocellulosic wet wastes. Typical mass conversion in anaerobic digesters is on the order of 40%–60%, leaving a significant fraction of the feedstock underutilized. With the primary exception of FOGs, many wastes contain significant fractions of lignocellulosics, which are disproportionately under-converted in standard AD processes, as other carbohydrates, lipids, and proteins are much more readily digested. Cellulose contents range from 13%–37% for manures, 20%–35% in sewage, and 40%–60% for MSW. Food service waste ranges from 2%–17% cellulose, with food processing wastes running much higher: approximately 35% cellulose in cattle rumen fiber and approximately 25%–35% in citrus waste. Depending on the digester and feedstock, 50%–70% of the cellulose may remain unconverted, representing a significant fraction of lost yield and potentially high-value cellulosic biofuel (D3) renewable identification number (RIN) credits.

Weighted Project Score: 8.2

Weighting for Ongoing Projects: Approach - 25%; Accomplishments and Progress - 25%; Relevance - 25%; Future Work - 25%



One standard deviation of reviewers' scores

Advances in hydrolysis of lignocellulosics in wet waste provides significant potential enhancements that will provide social and economic drivers for wet-waste conversion, including:

- Faster conversion rates for reduced footprint and capital costs
- Greater extent of hydrolysis for reduced waste volume, higher yield and titers of product, and increased D3 RIN credit potential
- Expanded feedstock range, reducing landfill volume and increased flexibility
- Applicability in many cases to both methanogenic and acidogenic anaerobic digestion.

This project is approximately 50% through its planned three-year timeline. During this time, we have developed collaborations with multiple industrial partners in the brewing, food processing, and water treatment industries. We have focused our efforts on digesting cattle rumen fiber (i.e., “paunch”) more effectively while focusing on reducing methane production and increasing VFA product titers. Rumen fiber is highly lignocellulosic and difficult to digest, so improvements will be applicable to other wet wastes containing lignocellulosics.

Technically, we have developed stable mixed consortia derived from multiple seed inocula that converts 50%–60% of the rumen fiber at 8% solids and producing 60%–65% methane. Cellulase augmentation enhances VFA production under low pH arrested methanogenesis conditions, while hemicellulase and laccase have mixed impacts. Thermomechanical pretreatment enhances VFA production fourfold when combined with enzyme augmentation. Elevated temperature or low pH leads to low VFA titers, as VFA inhibition of hydrolysis VFA production is a limiting factor when methanogenesis is arrested. Removal of VFAs during digestion results in approximately four times higher VFA production.

Photo courtesy of National Renewable Energy Laboratory

OVERALL IMPRESSIONS

- This is one of several projects focusing on the development of arrested AD for bioproduct generation instead of biogas. This project focuses specifically on improving cellulose conversion during the arrested AD process, with the hope of generating a higher yield of the desired VFA product at a higher rate. This work intends to use the separations technique being developed by a related NREL project (2.3.2.107), so the research being performed is consistent with the constraints required by this separation's technology (e.g., working at low pH). This project appears to have achieved considerable success in its research so far, achieving relatively high VFA titers as a result of a combination of several modifications made to the AD process (e.g., enzyme use, pretreatment, and removal of VFAs as they are formed). The remaining work on this project is all viable, yet ambitious in scope, and should be prioritized to ensure that the most promising tests are performed first with the remaining time available on this project. There also appears to be some overlap in the microbe consortium screening work with the other NREL team (2.3.2.107). While it is recognized that the two teams have performed their microbe research using different feedstocks, it is recommended that one team be responsible for future research in this area so as not to duplicate efforts and use time and monetary resources most efficiently if the intent is to find the most promising culture for the proposed arrested AD system. Because this project team (2.3.2.108) is looking at the most advanced conditions by incorporating cellulose hydrolysis, it is probably the one to lead the microbe consortium development work. A discussion on the actual current market value of the low-carbon VFA species being targeted relative to the base case of biogas generation in conventional AD is not provided, but should be because it is important in assessing whether the cost of the arrested AD process being developed has a chance at being economically viable.

- Good project with the potential to improve understanding of basic AD mechanisms. While the results may be considered obvious (e.g., hydrolysis as a rate-limiting step), attempts to quantify and correct AD digestion limiting factors have never been carried out systemically. It is not the first time that the potential benefit of pretreatment and enzyme addition has been discussed, yet this is probably a more fundamental and systemic approach to the analysis than most and uniquely couples the consideration of the role of microbial consortia. The main weakness of the project is still a relatively undeveloped TEA component—although mitigated by another project explicitly focusing on this—and the lack of distinct pathways to industrial implementation. Given the generality of the problem and the rather fundamental level at which the PIs are operating at this time, I do not consider this a significant problem and I think it can be addressed in due course at a more appropriate time.

RECIPIENT RESPONSE TO REVIEWER COMMENTS

- Thank you for the comments. We have been working with the separations task and have realized the overlap in certain areas. We are considering merging these efforts into a consolidated task, with resources from 2.3.2.108 being used to screen different feedstocks and consortia for increased VFAs/decreased methane. This will allow the 2.3.2.107 project resources to be focused on testing and enhancing the separations methodology and equipment. The combined tasks will be more efficient, and this will allow some resources to focus on improved analytical methods for characterizing the feedstock and residuals in order to gain a better understanding of the TEA.

- Thank you for pointing out the lack of understanding regarding the nature of the limiting factors in AD. Clearly, developing this knowledge will allow a more directed focus on the areas that are most impactful to the overall economics. Gaining a better, more expanded TEA analysis is a major need here and fundamental knowledge on AD limitations will enable improved and more relevant TEA.

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

National Renewable Energy Laboratory

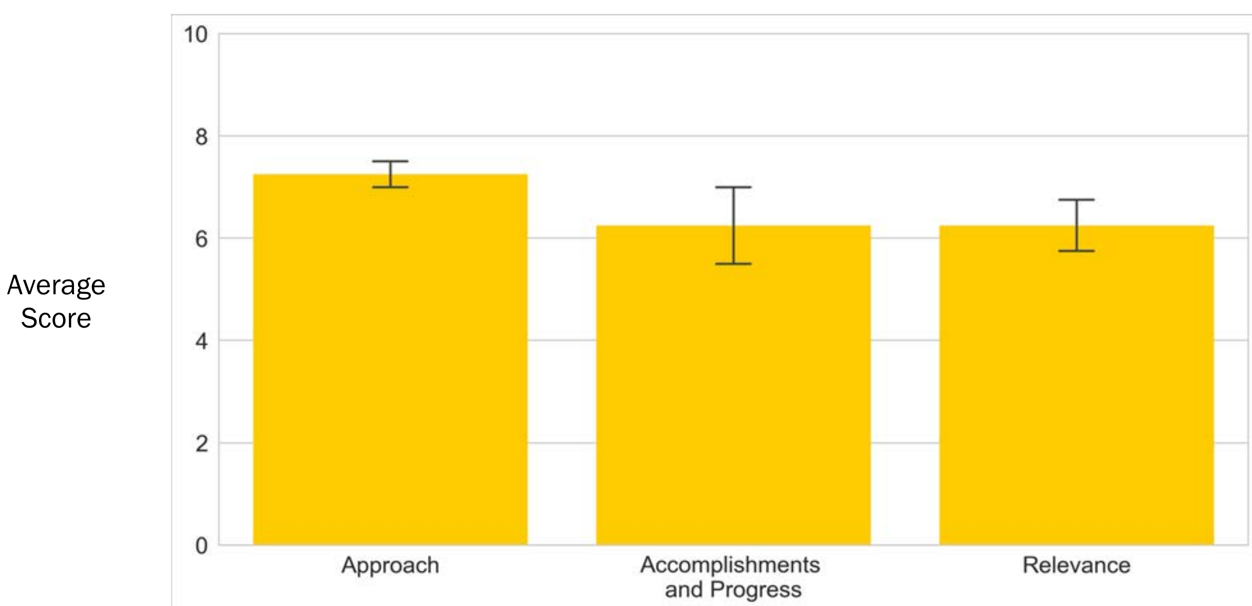
PROJECT DESCRIPTION

WBS:	2.3.2.201
CID:	EE0006877
Principal Investigator:	Dr. Mike Guarnieri
Period of Performance:	6/1/2015–9/30/2018
Total DOE Funding:	$2,241,411
Project Status:	Sunsetting

Biological methane conversion offers a scalable, modular, and selective approach to biogas upgrading. However, gas fermentation process intensification remains a primary hurdle in methane biocatalysis. To this end, the Biogas Valorization task targets the development of an integrated bioprocess to produce platform chemical intermediates from biogas. The project will integrate core competencies from government, industrial, and academic partners, including metabolic strain engineering, metabolic flux analysis, low power input bioreactor design, AD, and TEA in order to develop a conversion process demonstrating the production of organic acids from a renewable biogas feedstock stream. 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. This work is relevant to BETO's Multi-Year Plan (MYP) for developing cost-effective, integrated WtE processes to produce bioproducts, and it explicitly targets BETO MYP barriers, including catalyst development, biochemical conversion process integration, WtE roadmap hurdles, and process intensification.

Weighted Project Score: 6.5

Weighting for Sunsetting Projects: Approach - 25%; Accomplishments and Progress - 50%; Relevance - 25%



One standard deviation of reviewers' scores

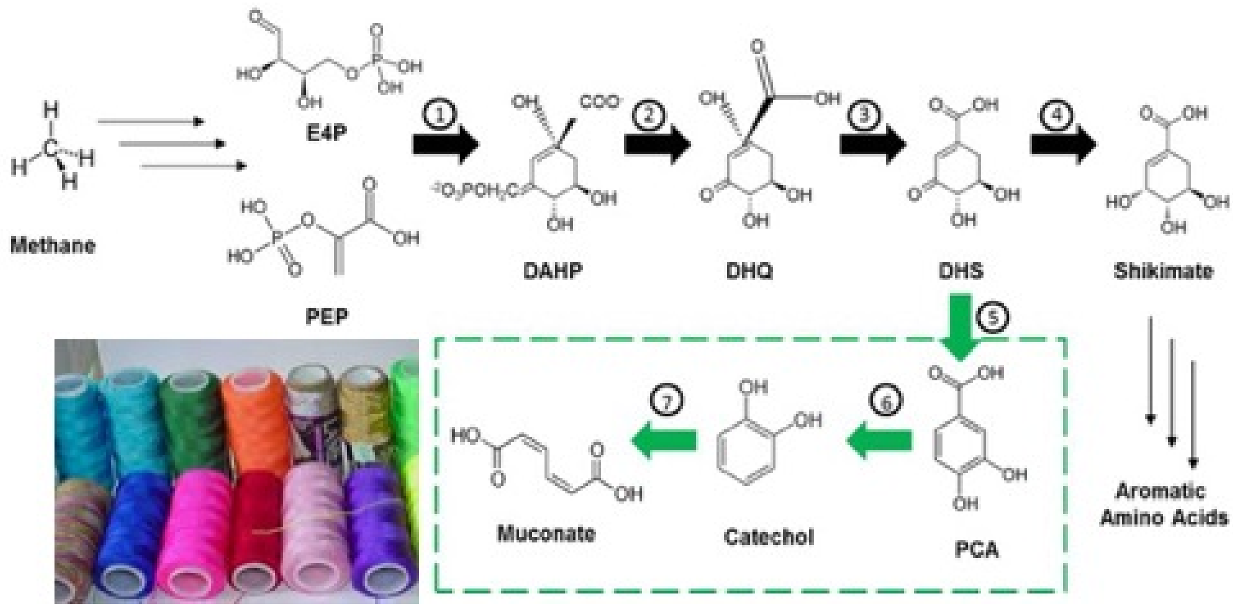


Photo courtesy of National Renewable Energy Laboratory

OVERALL IMPRESSIONS

- The intent of this project was to improve on conventional AD by converting the relatively low-value biogas produced by AD to a more high-value chemical intermediate product—muconic acid. Although the target yield of muconic acid ultimately could not be met due to constraints in the genetic structure of the methanotrophs used, there were several very valuable results that came out of the work in this project. First, the concept of muconic acid production from methanotrophs via genetic engineering was proven (just not at concentrations sufficient for scale-up). Second, reactor design advances led to a system that exhibited enhanced methane uptake and significantly improved mass transfer. Finally, although muconic acid could not be generated at acceptable concentrations, the project showed that succinic acid was produced at concentrations that may be high enough to be of commercial interest. Because succinic acid is a chemical that, like muconic acid, has broad applications in the chemical industry (e.g., as a precursor to many products and as a supplement in the food industry, to name a few), it would have been worthwhile to consider changing the focus on this project to generate succinic acid rather than termination. This is still something to consider for future work, if this potential is confirmed by an initial market study and/or TEA evaluation. Regardless, the information gained and lessons learned from this project in terms of genetic engineering of methanotrophs and associated reactor design should be able to be utilized and extended in future work, thereby making the current project successful from this perspective.

- The project was carried out in exemplary fashion with rigor, and while it did not achieve some of the original targets, the author pivoted and demonstrated feasible pathways with a new product and new reactor technology. Scalability issues remain to be addressed with the new immobilization concept presented.

- Although terminated, this project made significant technical advances in the configuration of bioreactors feeding on gas substrates. This technology will be picked up by other researchers and commercial companies for biological gas-to-liquid projects.

RECIPIENT RESPONSE TO REVIEWER COMMENTS

- We thank the reviewers for their complimentary and constructive commentary. We are pleased that, despite failing to meet productivity target metrics, efforts on this project achieved critical enhancements to gas mass transfer and process intensification for biogas fermentation processes. Thus, we agree that this project led to numerous valuable lessons learned and has laid the foundation for follow-on studies targeting alternative end products with more favorable biological compatibility. The resultant data have enabled important insights into methanotrophic metabolism and biogas cultivation capacity and led to the evaluation of three novel gas fermentation reactor configurations, each with unique characteristics that may be suitable for scalable deployment. Future efforts may entail piloting of reactor(s) at larger scales to determine scalability and lifetime, as well as comparative technical and techno-economic analyses to identify the most suitable reactor configuration as a function of target product and scalability. Importantly, the data generated from these efforts will provide critical inputs to complementary biogas biocatalysis projects focused upon microbial development and will inform pertinent metabolic engineering strategies. We also note the potential applicability of the design principles established here to conversion of an array of gaseous substrates, including CO_2, carbon monoxide (CO), and hydrogen (H_2). Thus, 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. We look forward to alternative opportunities to continue pursuit of this work.

BIOMETHANATION TO UPGRADE BIOGAS TO PIPELINE GRADE METHANE

National Renewable Energy Laboratory

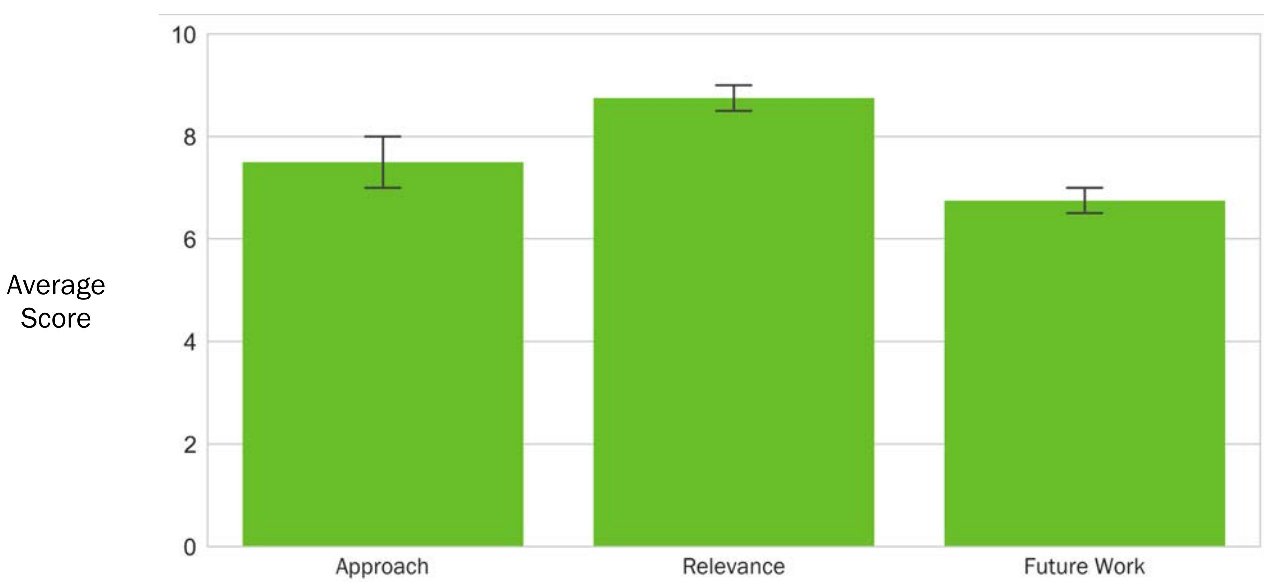
PROJECT DESCRIPTION

WBS:	5.1.3.102
CID:	NL0034005
Principal Investigator:	Dr. Kevin Harrison
Period of Performance:	6/1/2018–5/31/2021
Total DOE Funding:	$1,500,000
DOE Funding FY16:	$0
DOE Funding FY17:	$0
DOE Funding FY18:	$1,500,000
DOE Funding FY19:	$0
Project Status:	New

The move to renewable electricity sources is happening on a global scale to decarbonize the electricity sector. The biomethanation technology, being developed under this biopower project, intersects and can help solve many challenges we face by enabling higher penetrations of solar- and wind-generated electricity sources and leverages the DOE's fossil, nuclear, and renewable energy program initiatives like H2@Scale. This biomethanation process advances the concept of electrons to molecules by recycling and utilizing carbon and storing the renewable natural gas (RNG) in the existing natural gas network. Step one in the process requires low-cost, low-carbon, and otherwise curtailed electricity sources to produce low-cost hydrogen (H_2) from a water electrolysis system. Step two, the biomethanation process combines H_2 with a biogas source, containing CO_2, with single-celled biocatalysts to produce methane, water, and heat. The RNG requires very little cleanup to achieve pipeline-quality natural gas, which is then a direct "drop-in" replacement fuel injected alongside fossil-based natural gas. The RNG acts as a long-duration energy storage solution for renewable electricity sources and can help decarbonize the transportation sector at over 2,000 compressed and liquid natural gas stations across the United States.

Weighted Project Score: 7.4

Weighting for New Projects: Approach - 25%; Relevance - 25%; Future Work - 50%



One standard deviation of reviewers' scores

This project advances the science of scaling the biomethanation process from 700 L down to 30 L, enabling increased process development and progressing scientifically based scaling functions that will inform next-generation megawatt-scale bioreactor design and operation. The scaling functions will be applied to the utilization of biogas CO_2 from different sources with nutrient and controls optimization to accommodate varying biogas feedstock. Varying feedstocks will be investigated to understand the time and spatial composition differences of biogas sources from field sites across the country. Partnering with Southern California Gas (SoCalGas) provides guidance to map the technology for early-market opportunities at the megawatt scale. Electrochaea GmbH is supporting this project by providing in-depth process control, nutrient management, and a license to use the methanogen *Methanothermobacter thermautotrophicus*. Electrochaea is also supporting the development of advanced analytical methods for mass balances (e.g., carbon, nitrogen, sulfur, hydrogen, phosphorus), nutrient optimization, and the identification of potential coproducts produced by the methanogens under varying biogas conditions. The design and build of the pressurized 30-L scaled-down bioreactor will be based on the 700-L system provided by SoCalGas. This mobile 18-bar bioreactor system will overcome a significant challenge in developing this technology by traveling to actual biogas sites to perform research versus obtaining sufficient gas samples and transporting them back to NREL. Optimization and control of the gas feedstocks, nutrients, liquid levels, pressure, pH, and temperature will provide scientifically based scaling functions between the two systems. The project aims to demonstrate continuous operation of both bioreactors at pressures up to 18 bar using biogas feedstock (actual and synthetic) to produce a product gas composition capable of direct injection into the natural-gas network. In the end, this project will inform, guide, and enable megawatt-scale biogas upgrading through systems integration, reduced capital cost, and improved biocatalyst performance to accelerate the deployment and economics of WtE technologies using biogas sources.

OVERALL IMPRESSIONS

- This project aims to upgrade biogas (i.e., convert CO_2 in biogas to CH_4) using H_2 derived via electrolysis of water with renewable electricity from wind or solar power. On paper, this project has many significant benefits and great potential, including generation of a gaseous product equivalent to renewable natural gas, removal of CO_2 from the environment, and providing a market and use for excess wind and solar power. The design and operation of a mobile system is also an innovative approach that could be used to move the conversion technology to point sources of biogas for operation. The system, if successful, could be readily included as an "add-on" technology to existing waste conversion systems that generate biogas. However, there are some concerns with the project as described. Electrolysis is a very expensive way to make H_2 and the economics will heavily depend on the price of electricity. It is not clear how the project will ensure that the electricity it uses comes from renewable sources (emissions associated with electricity generated from fossil fuel would eliminate any benefit of CO_2 conversion in the process) at an acceptable price. Also, no information has been provided on how the H_2 will effectively be transported to the microbes, whether the microbes will be able to generate CH_4 to the concentrations desired (>97%), and how the product CH_4 will be fully recovered from the aqueous matrix. In addition, the need to perform more than one scale-up along with design, fabrication, and operation of the corresponding system during the three-year period of this project will be challenging.

- This is an excellent project showing good progress in the bioprocessing area with a good plan for field tests. This is highly relevant. I believe the project would benefit from deemphasizing the characterization of very different biogas streams and instead focus on establishing a realistic baseline to be achieved by using commercial off-the-shelf desulfurization technologies when necessary. The integration with the power network for efficient use of renewable energy resources needs more development. The TEA is, in general, wanting, as the potential for high capital cost is a significant risk for future deployment.

RECIPIENT RESPONSE TO REVIEWER COMMENTS

- The recipients choose not to respond to the reviewers' overall impressions of their project.

MODULAR MICROBIAL ELECTROMETHANOGENESIS FLOW REACTOR FOR BIOGAS UPGRADING

Lawrence Livermore National Laboratory

PROJECT DESCRIPTION

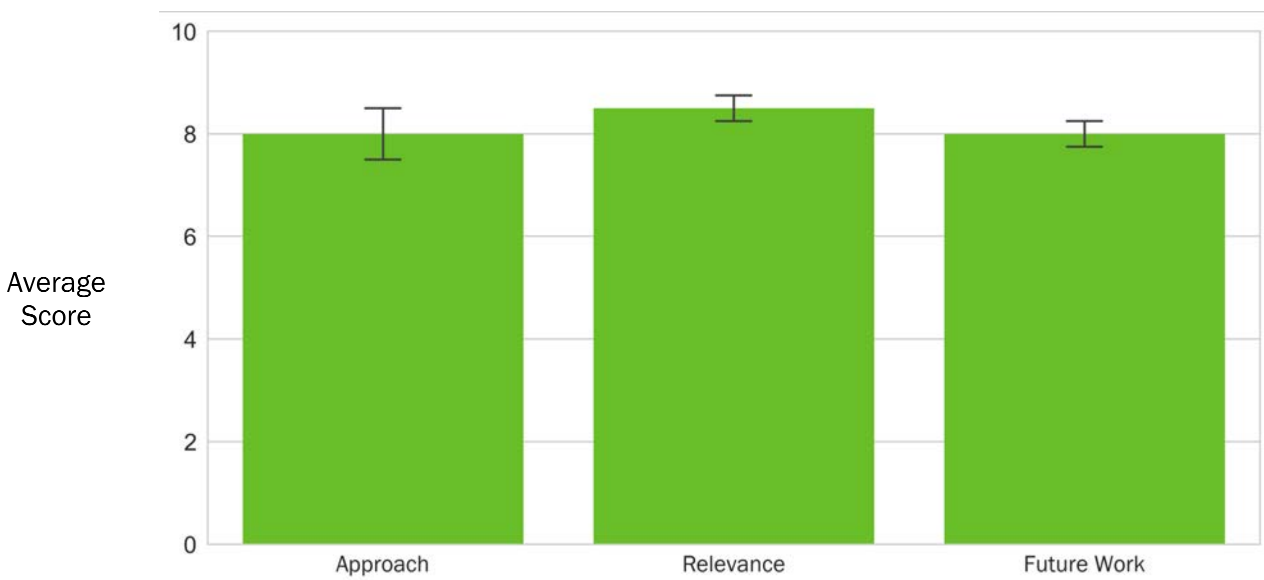
WBS:	5.1.3.104
CID:	NL0034001
Principal Investigator:	Dr. Sarah Baker
Period of Performance:	6/1/2018–5/31/2020
Total DOE Funding:	$800,000
DOE Funding FY16:	$0
DOE Funding FY17:	$0
DOE Funding FY18:	$800,000
DOE Funding FY19:	$0
Project Status:	New

The majority of the cost of biogas production is the removal of inerts (such as CO_2) and contaminants (H_2S, siloxanes). This cost is particularly prohibitive for small-scale biogas producers (e.g., dairy farms and feedlots), which collectively make up the majority of biogas potential. Technologies that remove CO_2 either vent it, contributing to greenhouse gas emissions, or must find an economical use for the gas, which is particularly difficult for small-scale producers. A more carbon-efficient approach is to convert the CO_2 to CH_4 in order to upgrade the gas to pipeline quality, rather than simply removing the CO_2. Methanation has the potential to be significantly more energy efficient and less capital intensive than CO_2-CH_4 separation, while virtually eliminating CO_2 emissions. Methanogenic microbes can utilize electrical energy to methanate CO_2 with high energy efficiency and selectivity. Additionally, this "electromethanogenesis" provides a pathway for storing electrical energy in chemical bonds for long-term storage of renewable electricity.

To unlock the potential of microbial electromethanogenesis for biogas upgrading and energy storage, Lawrence Livermore National Laboratory has partnered with Stanford University and SoCalGas, a major

Weighted Project Score: 8.1

Weighting for New Projects: Approach - 25%; Relevance - 25%; Future Work - 50%



One standard deviation of reviewers' scores

natural gas distributor, to develop a proof-of-concept reactor that upgrades biogas to pipeline-quality biomethane. To increase the maturity of the technology, the team will measure the effects of biogas composition and electrochemical reactor conditions on the productivity of electromethanogenic consortia, isolating strains that have high cell density under operation. Additionally, the team will use advanced manufacturing to generate high surface area electrode materials that reduce energy consumption, increase volumetric productivity, and have scalable surface area. The team targets a process energy efficiency of 0.03 g/Wh, based upon a TEA performed by SoCalGas, while producing pure biomethane. The team will also determine the overall process parameters necessary to generate biomethane at this target energy efficiency, including contaminant tolerances, biogas purity, and associated pre- and post-treatment requirements. These parameters will be used to conduct a TEA of the technology for biogas upgrading and power-to-gas applications, paving the way for larger-scale demonstrations.

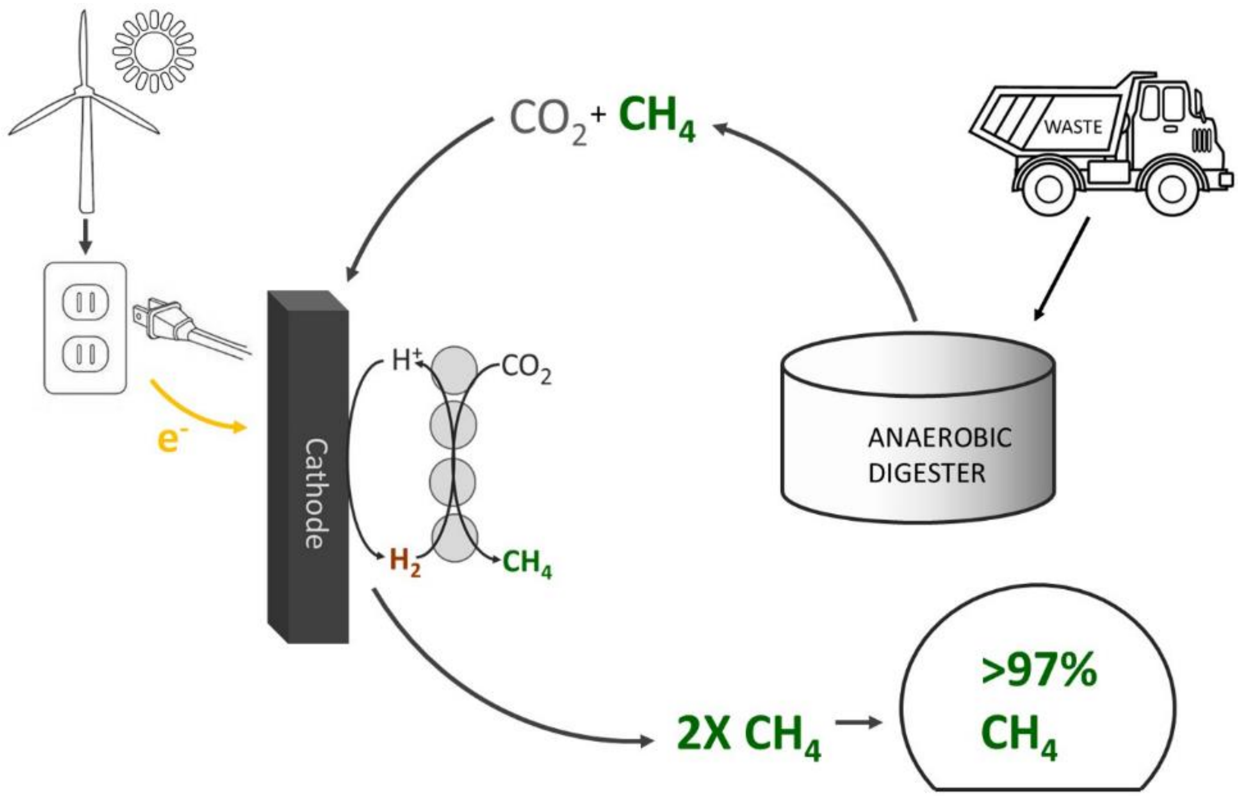


Photo courtesy of Lawrence Livermore National Laboratory

OVERALL IMPRESSIONS

- This project utilizes a combination of methanogenic microbes in an electrochemical cell to upgrade biogas to pipeline-quality natural gas. If successful, the benefits would include not only generation of fossil-quality gaseous fuel (of which it would help displace) but also a means to sequester CO_2. Though at an early stage, the project shows great potential in solving H_2 generation and transport issues by use of the reactor also functioning as an electrochemical cell, and through the use of innovative electrode materials (aerogels), which combine high surface area and porosity to bring the microbes and H_2 gas in close contact. However, as clearly shown in the presentation, there are a significant number of constraints in the system as designed and tradeoffs that will need to be considered in choosing the best microbe strains and material choices to withstand these constraints. The collective challenges make the success of this project anything but certain, but worth the investigation. Having SoCalGas as a partner is a good move for obtaining input with respect to end-user needs and other commercialization issues as the technical development of components occurs. This project lacks a discussion of costs, which is important to assess how economically viable this will be even if the technical challenges are overcome. In particular, it is expected that electricity costs will play a crucial role in this determination. To reap the full environmental benefits of this project, electricity will need to be obtained from renewable sources and not fossil-fuel-burning power plants, but there is no discussion on how this can be guaranteed. Also, there is very little discussion on how the TEA will be constructed and used with respect to the experimental data that will be generated. This presentation is also missing a schedule that shows how all of the described activities fit together relative to each other and with respect to project milestones.

- A good project that touches a very relevant biogas upgrading topic. Early to define in rigor scalability and economics, but more details—especially on what could be the capital cost of this type of reactor at scale—would be beneficial.

RECIPIENT RESPONSE TO REVIEWER COMMENTS

- We thank the reviewers for their time and constructive feedback. We agree that *in situ* production of hydrogen to generate reducing equivalents for methanogenesis may reduce energy and capital costs relative to systems that deliver gas-phase hydrogen to stirred-tank reactors. While the project is very early stage, based upon the reviewer comments we have initiated a TEA, which will help us make more informed decisions as the project progresses. The TEA will include a sensitivity analysis of the effects of electricity costs on operating expenses. We agree with the reviewers that if this project reaches pilot stage or higher TRL it needs to be proven with intermittent renewable energy to demonstrate maximum benefit. California curtailed 450,000 MWh in 2018, and renewable curtailments are projected to rise. Availability of renewable electricity and biogas will play a major role in choosing a pilot site. A project schedule was included in the peer-review slide deck; we apologize that we did not formally present it to the committee.

PRODUCTION OF METHANE FROM ORGANIC WASTE STREAMS WITH NOVEL BIOFILM-ENHANCED ANAEROBIC MEMBRANE BIOREACTORS

Argonne National Laboratory

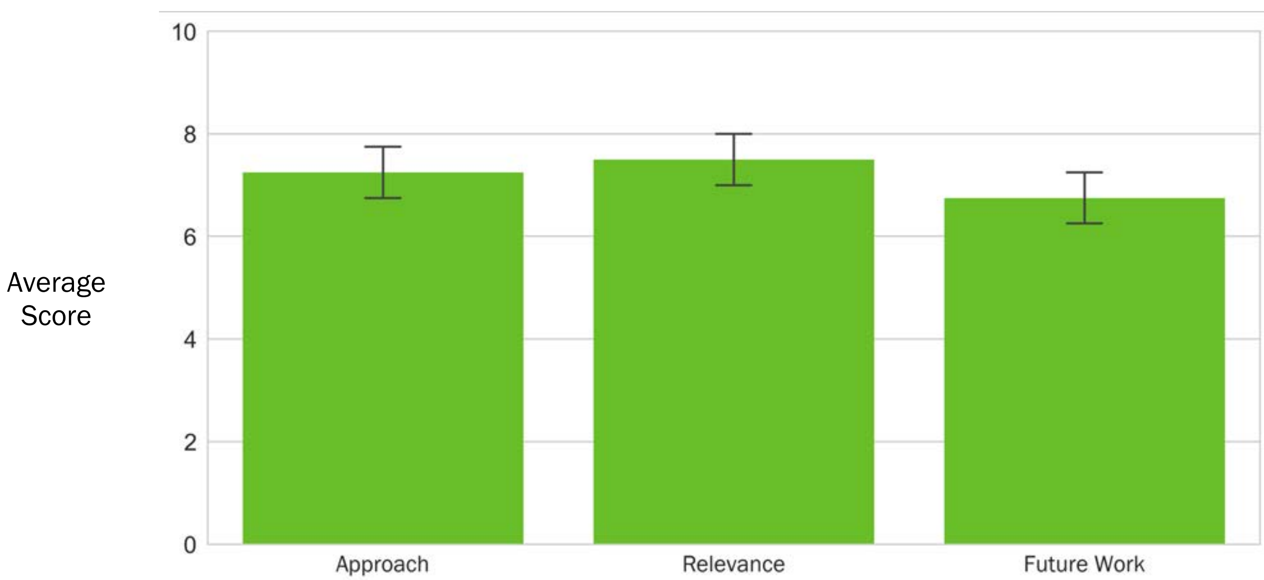
PROJECT DESCRIPTION

WBS:	5.1.3.105
CID:	NL0034002
Principal Investigator:	Dr. Meltem Urgun-Demirtas
Period of Performance:	5/1/2018–4/30/2021
Total DOE Funding:	$1,275,000
DOE Funding FY16:	$0
DOE Funding FY17:	$0
DOE Funding FY18:	$1,275,000
DOE Funding FY19:	$0
Project Status:	New

We have been developing an innovative, scalable anaerobic membrane biotechnology that converts organic waste streams into renewable methane using a two-stage novel anaerobic membrane bioreactor (AnMBR) system. The proposed research is motivated by the high volume of wet organic waste streams generated in the United States and has the potential to harness the associated energy. For example, estimates of yearly MSW generation in the United States vary from 254 to 347 million tonnes, of which 55% consists of food, paper, and yard waste. As AD converts organics into renewable methane, it is an ideal option for small decentralized communities or industries to locally treat their wastes and produce biopower. The AD capacity will likely increase in coming years. However, due to the economy of scale, biopower production for scales smaller than one ton/day currently is not economically feasible in the United States. Our ultimate aim is to develop a sustainable process that diverts an organic fraction of MSW (OFMSW) from landfills and incineration while generating renewable energy and capturing nutrients to meet the demands of organic waste generators and hauling companies.

Weighted Project Score: 7.1

Weighting for New Projects: Approach - 25%; Relevance - 25%; Future Work - 50%



One standard deviation of reviewers' scores

The project goals and targets are to improve the techno-economic viability of biopower production by developing a sustainable two-phase AnMBR system that diverts OFMSW from landfills and incineration while generating methane and renewable bioproducts. To achieve this goal, the proposed project entails five tasks:

1. Develop a flexible feedstock-blending plan for the urban organic waste streams produced by a typical U.S. city that meets treatment requirements and maximizes energy recovery while considering seasonal waste fluctuations

2. Develop a first-phase AnMBR inspired by the stomach physiology of ruminants that enhances hydrolysis and acidogenesis to maximize VFA production

3. Develop a second-phase AnMBR that exploits biofilm growth to enhance methanogenesis and optimize the conversion of VFAs to methane

4. Perform process simulation and analysis to model full-scale performance of the proposed technology.

5. Conduct TEA and LCA using the newly developed performance model to assess economic and environmental viability of our novel technology and further facilitate its implementation at full scale.

This project addresses BETO goals of developing economical and sustainable bioenergy systems by advancing efficient strategies for biofuels generation. We will develop and demonstrate proof of concept for a new methane production technology using organic waste streams generated in a typical U.S. city. Two novel biofilm-enhanced AnMBRs at TRL 4 will be developed and integrated as a two-phase system to facilitate high methane yields and low carbon footprints. The outcomes of this project are:

- A scalable, high performance, low-cost, two-phase modular AnMBR technology at TRL 4 that has the potential to extend the economic viability of AD to smaller scales

- Linkage between waste characteristics, microbial community structure, methane yield and recovery, and design and operation of the AnMBRs

- Updated GREET LCA model addressing energy and environmental benefits of new technologies from organic waste streams

- Development of new process modeling tools for AD of OFMSW.

OVERALL IMPRESSIONS

- This project proposes several modifications to the conventional AD process in order to improve the yield and methane production rates. Splitting the AD process so that it takes place over two reactors instead of one appears to be a good idea in that each reactor can be run at separate conditions more conducive to the steps in the AD mechanism that will occur in them (hydrolysis, acidogenesis, and acetogenesis steps in the first reactor, and the methanation step in the second reactor). The downside is that it increases the process cost and complexity, so that the improved performance will need to offset this increase in order to justify the project's value. The nature of the proposed changes to the AD process make it likely that the proposed improvements, if successful, could not be easily "bolted on" to existing AD systems. The design of the first reactor based on the bovine rumen and the intent to focus on underutilized food waste and the organic portion of MSW as a feedstock are also very good aspects of this project. More details on the two reactor system scale-ups that are proposed over the course of this project are needed to assess whether there will be sufficient time for this ambitious plan. While improvements in efficiency to any bioenergy process are valuable, the focus on AD does not appear to be one of the high priority stated goals of BETO.

- I struggled with this project as I am not quite sure what the overarching goal was. Develop a new (cheaper, better-performing, more compact, etc.) reactor? Develop arrested digestion? Increased gas production? Maximize feedstock flexibility? Make AD feasible at lower scale than conventional approaches? These are all valuable points but somewhat confusing in the way it is presented today. While it may be too early for detailed TEA, if the PIs do not know their possible economics, then they should at least know the targets they aim to beat.
- I would recommend an outreach strategy to report the successful outcome of this project to associations of sanitation agencies, landfill operators, and food processing plant owners in a case study description of an emerging technology.

RECIPIENT RESPONSE TO REVIEWER COMMENTS

- Our initial results showed that the first-stage anaerobic digester has achieved very good performance with a hydraulic retention time (HRT) of only 12 hours instead of days (usually 3–10 days). Therefore, capital cost will not be as high as conventional two-stage systems. While we partially agree that the operation of two-phase systems can be little bit more complex than conventional one-phase systems, the two-stage configuration has been considered as a viable approach to improve the overall AD performance in terms of biodegradation, rates, process stability, biogas yield, and energy recovery. Because of the short HRT, the new one-phase system developed in this project can be a 2–20-times smaller footprint than a conventional one-phase system. Also, both the first-phase and second-phase system developed in this project are anaerobic bioreactors that rely on dynamic membranes operated at lower transmembrane pressure and are made of cheaper materials than that of micro- and ultrafiltration-based membrane reactors. Hence, new technology will exhibit lower operational costs and less complexity compared to conventional AnMBRs. AD and membrane-based technologies are very well known and can be easily scaled up from bench to pilot scale. The project team believes that a three-year project duration would be sufficient to scale up the modular AD technology. This project, selected from BETO Funding Opportunity Announcement (DE-FOA-0001085) entitled "Lab Call for Biopower R&D (DE-LC-000L045)." In this call, "Topic 4: Alternative Approaches to Anaerobic Digestion" was specifically related with improvement of the techno-economic viability of AD at scales of one dry ton/day. The lab call also required the development of new technologies to overcome current challenges to efficient AD operation, including the energy requirements of minimizing membrane fouling and recovery of dissolved methane in the effluent at scales that match feedstock availability. Therefore, our first aim is to develop a techno-economically viable process at small scale, then consider the application of this process into existing AD systems, which usually consist of multiple ADs.
- The goal of this project is to make AD economically feasible for small-scale operation by addressing the challenges that prevent the application of this technology at scales of one dry ton/day. In order to do this, challenges related to the slow rate of the anaerobic degradation of waste, low methane yield and methane loss in the effluent, and the demand for processes handling of a diverse feedstock need to be addressed. The novel design of the two-stage bioreactors has focused on addressing challenges with (1) the rate of hydrolysis by using rumen microbial cultures and mimicking rumen operations, (2) low methane yield by long sludge (cell) retention time and separation of hydrolysis/acidogenesis from methanogenesis, and (3) sustainable feedstock supply requirement by developing a feedstock blending plan. Regarding the economics, conventional digesters operate at HRTs of 20–40 days. Our system will operate at a total (first and second phase combined) HRT of 4–5 days, which means that capital costs have the potential to be reduced by 2–10 times. Operational costs are also expected to be lower than conventional AnMBRs, but not conventional AD systems, due to the simplicity of operating a dynamic membrane compared to microfiltration membranes. Conventional AD systems without membranes are simpler than our system.
- As mentioned throughout the presentation, the targets are the production of VFAs at a yield of 0.35 g/volatile solids in phase 1 AnMBR and methane with a yield of 0.4 liter/g volatile solids fed on a

sustainable basis in two-phase ANMBR system. These targeted values were taken from the literature reported for the cost-effective production of methane from organic waste streams.

- Our business project partners are Metropolitan Water Reclamation District of Greater Chicago, which operates seven wastewater treatment plants in the Chicago area; Gray Brothers LLC, which is a waste hauler and a landfill operator in Pennsylvania; and Roeslein Alternative Energy, which produces and injects renewable methane produced from manure and agricultural waste streams. We also plan to publish our results in technical papers and present them at the conferences to disseminate the results as a part of our outreach efforts. With respect to the suggested outreach strategy in the comments, we plan to identify additional waste generators, landfill operators, facilities, and AD users where this technology can be applicable to meet stakeholder needs moving forward.