ORGANIC WASTES

TECHNOLOGY AREA

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INTRODUCTION

The Organic Waste Conversion Technology Area is one of 12 technology areas that were reviewed during the 2021 Bioenergy Technologies Office (BETO) Project Peer Review, which took place virtually March 8–12, 15–16, and 22–26, 2021. A total of 16 presentations were reviewed in the Organic Waste Conversion session by five external experts from industry, academia, and nonprofit areas. For information about the structure, strategy, and implementation of the technology area and its relation to BETO's overall mission, please refer the corresponding program and technology area overview presentation slide decks, which can be accessed here: https://www.energy.gov/eere/bioenergy/2021-project-peer-review-organic-waste.

This review addressed a total U.S. Department of Energy (DOE) investment value of $27,857,121, which represents approximately 4% of the BETO portfolio reviewed during the 2021 Peer Review. During the Project Peer Review meeting, the presenter for each project was given 35 minutes to deliver a presentation and respond to questions from the Review Panel.

Projects were evaluated and scored for their project management, approach, impact, and progress and outcomes. This section of the report contains the Review Panel Summary Report, the Technology Area Programmatic Response, and the full results of the Project Review, including scoring information for each project, comments from each reviewer, and the response provided by the project team.

BETO designated Beau Hoffman as the Organic Waste Conversion Technology Area Review Lead, with contractor support from Mark Philbrick (AST). In this capacity, Beau Hoffman was responsible for all aspects of review planning and implementation.

ORGANIC WASTE CONVERSION OVERVIEW

The term "waste to energy" (WTE) typically refers to any number of mature technologies, especially incineration or anaerobic digestion (AD), that are utilized as a means to reduce waste volumes. In the context of this section, BETO defines "organic waste" as municipal wastewater residues; manures; food waste; fats, oils, and greases; and biogas derived from the breakdown of these waste streams. Other technology area sections explored other waste streams such as other fractions of municipal solid waste (Feedstock Technologies session) and plastics (Plastics Conversion session).

Organic waste represents an existing and growing economic, environmental, and social liability across the United States. Landfill disposal fees continue to increase year over year, and many municipalities and communities have to bear high costs to dewater, stabilize/sterilize, and transport these waste streams. In some cases, due to landfill organic diversion regulations, organic waste is transported across state lines. These waste feedstocks are also a growing environmental concern. When these waste streams break down in landfills or in other systems, they often evolve into biogas (a mixture of methane and carbon dioxide [CO_2]), which is significantly more potent than carbon dioxide alone as a greenhouse gas. According to the U.S. Environmental Protection Agency, landfills, manure management, and wastewater treatment plants account for more than 230 million metric tons of carbon dioxide equivalent per year.

These organic waste streams are also a social sustainability liability. Although organic waste is generated by all members of society, in many communities, solid waste handling infrastructure is located in disadvantaged communities. Thus, these disadvantaged communities must bear a disproportionate amount of the burden associated with these facilities. These include odors from facilities, noise, pollution and particulate emissions due to transportation of these wastes, accumulation of litter, and prevalence of infectious disease vectors (especially rodents and mosquitos), among others. In this regard, it is critical that next-generation resource and energy recovery facilities from waste are designed with these indicators in mind. Moreover, the piloting and deployment of these technologies must be mindful of emerging indicators and impacts, including social acceptance and license to operate.

The presentations in the Organic Waste Conversion Technology Area were organized into five thematic areas: Analysis, Liquid Fuels from Waste, Chemicals/Products from Waste, Improvements to Anaerobic Digestion, and Renewable Natural Gas.

Analysis projects comprise DOE national laboratory projects that are seeking to quantify the abundance and current practices associated with these organic waste streams. This includes quantifying current beneficial uses (e.g., composting) and the costs associated with handling these waste streams. Techno-economic analysis (TEA) is also included in this thematic area to evaluate the costs/benefits of particular resource and energy recovery approaches.

Liquid Fuels from Waste projects explore experimental research and development (R&D) to convert organic waste streams into hydrocarbon fuels. This thematic area includes projects from both national laboratories and academic institutions using technologies such as hydrothermal liquefaction and arrested anaerobic digestion.

Chemicals/Products from Waste projects explore experimental R&D to convert organic waste streams into high-value bioproducts and biochemicals. BETO recognizes that the market values of these bioproducts and biochemicals are often significantly higher than commodity fuels, and processes that are able to obtain higher revenues per unit produced may have more near-term market penetration. This thematic area includes projects from national laboratories, industry partners, and academic institutions.

Improvements to Anaerobic Digestion projects explore experimental R&D to improve yields and/or reduce capital intensity of anerobic digestion. Anaerobic digestion is commonly employed as a strategy for converting waste into biogas, but is often not economically viable at small scales (especially less than 5 dry tons of organic matter/day). National laboratory and academic institutions are exploring processes that can reduce these capital and operating costs through technologies such as thermal pretreatment and novel anaerobic digester design.

Finally, the Renewable Natural Gas projects explore experimental R&D to economically convert biogas into renewable natural gas that is compatible with the existing natural gas infrastructure. While there are incumbent technologies for accomplishing this cleanup step, they are operationally intensive. National laboratory and academic institutions are also exploring processes that can increase the availability of renewable natural through power-to-gas technologies.

ORGANIC WASTE CONVERSION REVIEW PANEL

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ORGANIC WASTE CONVERSION REVIEW PANEL SUMMARY REPORT

Prepared by the Organic Waste Conversion Review Panel

INTRODUCTION

This report summarizes the comments and observations from the members of the 2021 Project Peer Review Panel. The Organic Waste Conversion panel reviewed a total of 16 projects during the 2021 Project Peer Review meetings on March 9 and 10, 2021—an increase of one from the previously named Waste-to-Energy Panel during the 2019 Peer Review. The technologies included in the 2021 Peer Review were hydrothermal liquefaction, arrested methanogenesis, processes to improve biogas production and/or increase biogas quantities through CO_2 conversion, and microbial electromethanogenesis.

BETO began to evaluate projects associated with converting waste products to energy in 2017. The 2019 Peer Review Panel recommended that BETO expand the definition of waste. The material now defined as waste includes municipal sludge residuals, animal manure (mostly swine and dairy), organic fraction of municipal solid waste (food waste and yard debris), and inedible fats/oils/greases. BETO estimates that 27.52 million dry tons of these wastes are producing 3.979 billion gallons of gasoline equivalent (GGE). They further estimate an additional 49.65 million dry tons remaining, which can produce 5.312 billion GGE.[1] The conversion of these wastes to energy increases the renewable energy portfolio and potentially reduces cost and solves several environmental problems, including greenhouse gas emissions from landfills and transporting these wastes over long distances.

Additionally, because of problems associated with per- and polyfluoroalkyl substances (PFAS), many water resource recovery facilities (WRRFs) are facing a crisis concerning disposal of digestate produced from the AD process. Typically, this material would be land-applied as a fertilizer, but many states are banning or considering banning that practice. Biogas production from AD is a significant renewable energy source for these facilities, and therefore it is important to develop processes that can convert digestate to energy while destroying PFAS. This problem is not currently directly addressed in the BETO program, but some of the technologies being investigated may have the potential to transform or destroy PFAS. BETO estimates that 14.8 million dry tons of untreated municipal sludge are produced each year in the United States, representing a potential of 2 billion GGE.

The biggest challenge is the ability to use these mixed wastes and the logistics of transporting these materials to a blending facility. Some of the challenges include the mechanics of blending, removal of contaminants, ability to produce a feedstock with consistent characteristics, and disposal of any waste solids or liquids produced during energy recovery. Many of the liquid side streams have high concentrations of ammonia-nitrogen or contaminants of emerging concern (again, including PFAS), which will necessitate treatment and can impact eventual adoption.

STRATEGY

The Review Panel feels that the technology area has a well-defined mission and set of goals and technical targets. This program appears to recognize and support technologies that make the most sense and potentially generate liquid fuels/products from wet-waste feeds. The strategy to focus on wet-waste biomass to liquid fuels or products at a chosen target price (e.g., $3/GGE by 2022) in conjunction with greenhouse gas emissions reduction (e.g., 60%) is simple and direct and hits the key issues (waste conversion and greenhouse gases) with clear and direct targets. BETO has undertaken a rigorous process of technology review and is diligent in its selections to ensure the highest level of innovation has the chance to be achieved within the time and resource constraints of the project. All of the projects have value in advancing BETO's goals, and many contain highly

[1] https://www.energy.gov/sites/default/files/2017/09/f36/biofuels_and_bioproducts_from_wet_and_gaseous_waste_streams_full_report.pdf

innovative or unique aspects. Most appear to be making reasonable progress toward their objectives and have appropriate management.

Most projects appear to have recognized the importance of including industry partners and other relevant stakeholders within their project team, and many have identified and included critical ones to cover all major areas in their project (e.g., waste feed handlers, manufacturers of key equipment, companies trying to commercialize the core technology). Because there appears to be a heavy weighting toward national lab and university-led projects, such partners can provide important guidance to help ensure that research efforts focus on relevant issues and in ways that will increase the probability of industry acceptance and economic viability. The program could be improved by gaining stronger engagement, and even leadership, from commercial and industry partners. These partners will likely bring more rapid assessment of commercial validation for the technology advancements and help guide the research groups early on toward outcomes that complement market opportunities.

There do not appear to be any major gaps in the technologies pursued by BETO with respect to their funding; nevertheless, one possible gap may be the use of supercritical water gasification as a means of hydrogen generation, which should be explored. Like hydrothermal liquefaction (HTL), supercritical water gasification is ideal for aqueous organic wastes. Unlike “dry” gasification, the presence of water favors hydrogen production due to the water-gas shift reaction. Several projects in the current program rely on hydrogen produced by electrolysis of water, which in turn limits the source of energy needed (which is considerable) to renewable sources. This may be hard to ensure. Supercritical water gasification may be a relatively less expensive and less restrictive way to generate hydrogen in situ and may be worth exploring.

The appropriate funding mechanisms are being used. Consideration should be given to structuring funding opportunity announcements/grants so as to encourage involvement of private entities. Funding the laboratories using the annual operating plan has allowed for a broad range of research topics. BETO might want to consider a two-pronged approach of casting a broad net for new innovations while simultaneously using the results of the current set of projects to narrow future funding opportunities to further advance those technologies that have demonstrated the most potential in meeting its goals. BETO should consider a dedicated funding opportunity announcement focusing on the management and characterization of the waste streams that come from the new technologies/systems that are a focus of further development. Indeed, the Review Panel identified potential problems associated with both liquid and solids side streams from these processes that do not appear to be addressed at present. In addition, since the focus is on reaching specific cost targets consistent with commercial development, BETO should consider that universities might be better suited to make contributions to new innovations since they are primarily geared toward fundamental research and may not have the capacity to achieve commercial viability unless they have strong commercial partners.

STRATEGY IMPLEMENTATION AND PROGRESS

In general, the technologies currently being investigated are aligned with the program strategy. The projects that focus on liquid fuel/product generation or greenhouse gas reduction such as HTL, arrested AD, or biogas upgrading all directly support BETO’s goals. Projects that focus on improving AD and biogas generation do not appear to be as relevant to the main strategy of this session and the Conversion Technologies Program, but the importance of these projects is nevertheless understandable since AD is so widespread and improved efficiency is beneficial. There were also funded projects that focused on feedstock availability, quantification, and geographical distribution that the Review Panel also deemed important. Analysis of feedstock potential and understanding the variability and availability of feedstocks are critical aspects in supporting technology goals and the economic and commercial viability of the investigated technologies. These projects also provide critical input criteria for future innovations.

Most projects appear to have one or more innovative or unique approaches that make them worth studying and qualify them as leading-edge. There is some degree of duplication of efforts, particularly with the arrested AD and biogas improvement projects, but this is important as none of the technologies are full-scale yet. Projects for upgrading methane using either biomethanation or microbial electromethanogenesis are very innovative and relevant to the program goals, can be coupled with existing AD facilities, and have produced very good results. HTL remains among the most promising opportunities for wet organic feedstocks. There are still no full-scale systems operating, however, and without implementation in real-world situations, it is impossible to determine if the technology will perform as intended. For all technologies, it is important to work on aspects related to scale-up through documented collaborations with industry. Identifying a pathway to handing over some of these technologies once they are past R&D, but still funding scale-up work with industrial, community, or government partners as appropriate to de-risk innovation, may be an option worth exploring (public-private partnerships, partnerships with utilities, etc.). This may require tighter links between the R&D efforts and users and companies specializing in commercialization, even in early stages of the research.

In some cases, it appeared that the research was not performed with final to-scale operation in mind. Examples of attributes that were not well understood include capital cost or operating cost limitations to different geographies or different plant sizes, market drivers and limitations that steer commercial players toward or away from applying new technologies, difficulties or constraints in managing side streams and waste streams from the processes, and the need for a consistent mix of feedstocks. Although these considerations are not appropriate focal areas for every project, it is important for BETO to consider addressing these attributes within the funding portfolio as a whole. Most projects appear to be making steady progress consistent with their project timeline.

Some project teams predict meeting or beating the $3/GGE minimum fuel selling price (MFSP) target for liquid fuels, which is better than expected at this point. Not all of the component conditions that go into calculating MFSP values have been fully demonstrated or validated, however (e.g., requiring operation at a scale that is orders of magnitude greater than current capability), which diminishes the validity of these claims in some cases.

BETO project management appears to be providing sufficient oversight to enable good progress. Many projects cited helpful interactions with BETO staff, and no projects appeared to be in jeopardy or struggling in a way that might otherwise suggest inadequate supervision. It is evident that BETO undertakes a rigorous process of technology review and is diligent in their selection of projects to ensure the highest level of innovation and success within the time and resource constraints of each project.

RECOMMENDATIONS

This portion of the report is divided into two topics: (1) top recommendations on how the portfolio could be strengthened and (2) recommendations on improving the peer-review process.

Strengthening the Portfolio

As mentioned earlier, the Review Panel recommends a stronger role for commercial and industrial partners. These partners can bring more rapid assessment of commercial viability of technology advancements and help guide the research groups early on toward more favorable outcomes that complement market opportunities. The research teams are performing innovative and high-quality research; nevertheless, it was evident that in some cases the research did not consider how this innovation could be commercialized and issues associated with operations and side-stream management and disposal. Further investigation into the intersection of innovation and commercialization by BETO may help more efficiently transfer technology platforms developed within these projects to industrial application, with stronger stakeholder partnerships helping to move these projects from lab scale to full scale to mainstream. Likewise, with projects that combine multiple unit operations, additional emphasis should be placed on ensuring demonstration, even at a pre-pilot or pilot scale, of the integrated process. Integrated operation and the ability to scale up successfully are critical and should receive more emphasis. Furthermore, the Review Panel recommends that DOE add criteria to ensure PFAS destruction/removal is considered in future funded projects.

BETO should be careful not to let achieving overarching target metrics such as the MFSP override the more important focus of demonstrating solid technical development and progress. Too much attention on meeting a specific number encourages projects to play with hypothetical scenarios for their technology just to say they can meet the target when they are not at a technology readiness level where these claims can be verified. Targets that focus on energy return on investment or levelized cost of energy are a bit esoteric and nonintuitive.

One critical area that should receive greater attention is the dissemination of the research advances with a focus on adoption. There should be a concerted effort (maybe through connections with state governments, target counties, large wastewater treatment plants, large municipalities, municipalities targeted as “hubs,” municipalities identified as “early adopters” of new technology, etc.) to educate decision makers on the entire picture (TEA, logistics, technology, etc.) so that large-scale goals of the United States, DOE, and BETO can be realized more effectively without individual projects having to develop their own (disconnected) partnerships. Working with industry and target municipalities to move larger DOE and BETO ideas (regional waste-blending hubs) and technologies forward and de-risk them further is critical and would be more efficient and successful if coordinated centrally.

Review Process

The panel strongly recommends a change in the review process. During the presentations, a considerable amount of time is spent on the organization and management structure of the projects, minimizing the time available for discussion of the technical aspects of the projects. The panel recommends that BETO continues to provide, in advance, the entire slide deck, but that the actual presentation be limited to the technical details, focusing on goals, process flow diagrams and material balances, research approach, results, and outcomes.

The panel understands and respects the proprietary aspects of these projects; nevertheless, BETO should ensure that a sufficient level of detail and data is provided to the reviewers to understand the process and accurately assess progress. More time needs to be allocated to reviewer questions and better enforcement of the time limit given to the technology presentations. Finally, it is important for reviewers to be able to record their observations when impressions are fresh; therefore, time needs to be provided for this after each presentation.

ORGANIC WASTE CONVERSION PROGRAMMATIC RESPONSE

INTRODUCTION

The Conversion R&D Program Area would like to first thank the five Organic Waste Conversion reviewers for their time and careful review of the portfolio and the projects therein.

The Review Panel notes several concerns and issues with the review process. BETO notes some of the comments and suggestions for improving the effectiveness of the event and quality of the feedback in the future.

The Review Panel notes several other technical themes. Reviewers noted that PFAS are an emerging contaminant of concern and are particularly prevalent in several of the organic waste streams that are focal areas of the Organic Waste Conversion section. The science associated with the origin, fates, and analytics to detect these compounds is evolving rapidly. Compounding this complexity is the emergence of new conversion technologies such as hydrothermal liquefaction. Thus, BETO is exploring the extent to which these fluorinated species are degraded and what these species degrade into. Another theme and potential need is to explore the consequences of the side streams that are produced from these processes. This is an important suggestion and one that BETO will consider as the portfolio continues to evolve.

The following section specifically addresses the top recommendations from the Review Panel:

Recommendation 1: Scale-Up and Integration Research Challenges

BETO would like to thank the reviewers for this recommendation. Recent R&D priorities have been focused on early-stage research and development at lower technology readiness levels. In crafting a portfolio, the BETO team has sought to create a pipeline for next-generation waste-to-energy processes. While several technologies have encountered challenges, other processes have overcome key technical barriers that indicate they are ready for scale-up. There are some technical barriers that can only be addressed at certain scales and levels of integration.

As noted above, one specific technical challenge that is critical is the generation of side streams and byproduct streams. For organic waste conversion, a key driver is waste volume reduction. If processes are producing waste streams that are more toxic or challenging to manage than incumbent processes, the technology has little chance of success. To this end, BETO will direct higher-technology-readiness-level projects to consider the side streams that are being generated and the strategies for mitigating them.

The Conversion R&D Program is also engaging in a broader effort to “graduate” technologies into the Systems Development and Integration Program to address some of the research-at-scale challenges. Already, several technologies developed under the Organic Waste portfolio have started to make the transition to pilot scale, such as T2C-Energy (landfill gas upgrading), HYPOWERS (hydrothermal liquefaction), and efforts in biomethanation.

Recommendation 2: Increased Emphasis on Industrial/Community Involvement in Projects

The Review Panel noted that commercial or industrial advisory boards could enhance the impact of the research being conducted. BETO fully concurs with this recommendation, particularly for projects led by the national laboratories or institutes of higher education. From several of the recent funding opportunity announcements, BETO staff has observed that the quality of the projects and relevance of the work is significantly enhanced on projects that include commercial partners, utilities, communities, and others. BETO will consider ways to emphasize this in future funding opportunity announcements as merit review criteria.

BETO also appreciates the comments that “there should be a concerted effort (maybe through connections with state governments, target counties, large wastewater treatment plants, large municipalities, municipalities targeted as ‘hubs,’ municipalities identified as ‘early adopters’ of new technology, etc.) to educate decision makers on the entire picture…” Indeed, this is a key objective of the recently launched Waste-to-Energy Technical Assistance for Local Governments program. At the time of preparing this response, BETO has already initiated five of these community partnerships, and it is proving to be a very successful method of disseminating analyses to local decision makers while simultaneously gaining insight into the local priorities and challenges of these communities. BETO has requested additional funds in fiscal year (FY) 2022 for this activity given the successes and benefits observed thus far.

Recommendation 3: Consider Relevance of Metrics

BETO concurs that being overly prescriptive in defining metrics can cause projects to get distracted from the main objective of the applied research, which is to advance the technology readiness levels. This is an important suggestion and could represent an opportunity to improve future funding opportunity announcements and address some of the other recommendations such as preparing a technology for piloting. In particular, levelized cost of energy and energy return on investment metrics will be used judiciously. For applied R&D topics, BETO will emphasize metrics that display technology and systems readiness such as continuous time on stream, catalyst lifetime, and degree of process integration, among others.

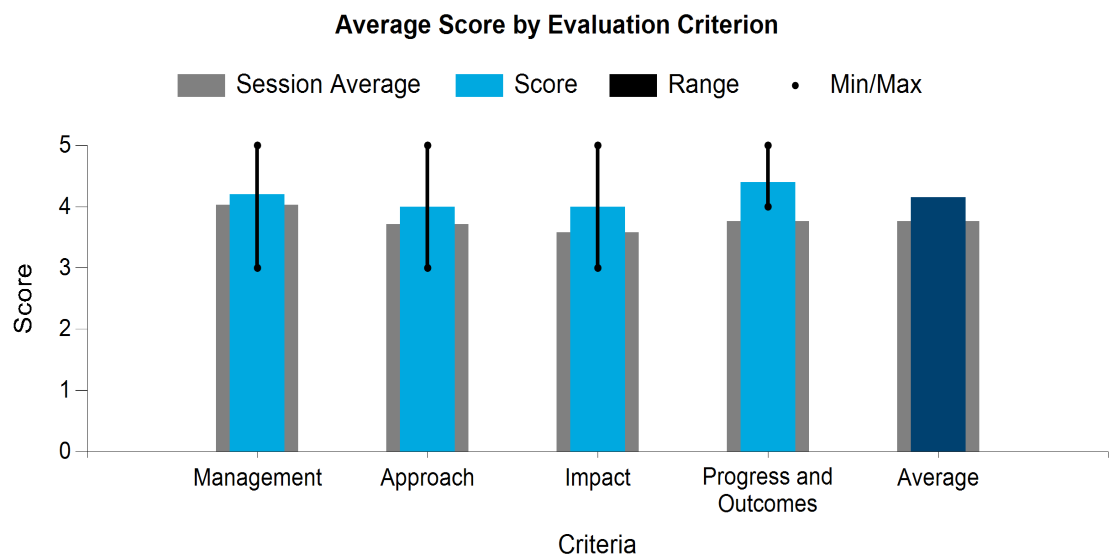
WASTE TO ENERGY: FEEDSTOCK EVALUATION AND BIOFUELS PRODUCTION POTENTIAL

National Renewable Energy Laboratory

PROJECT DESCRIPTION

WBS:	2.1.0.112
Presenter(s):	Adam Bratis; Anelia Milbrandt; Zia Abdullah; Courtney Payne; Jessica Krupa
Project Start Date:	05/01/2015
Planned Project End Date:	03/31/2021
Total DOE Funding:	$975,000

The goal of this project is to provide foundational data, strategic analyses, and outreach related to waste resources to support further development of the WTE industry. It builds on previous project outcomes, such as estimates of quantity, geographic distribution, and prices of wet-waste resources (food waste, sludge, manure, waste fats, and oils). The project provides better understanding of the waste resources potential and economic viability to enable development of new technologies and support strategic decisions. Challenges associated with this project are related to data availability (e.g., gaps in municipal solid waste [MSW] composition data) and data quality (e.g., inconsistent MSW composition definitions). All FY 2019 and FY 2020 milestones in the project management plan have been completed. Major accomplishments include: (1) cost-benefit analysis for 21 food waste disposal and utilization pathways, (2) detailed assessment of select MSW streams (plastics, paper/cardboard, and wood) at a fine geographic level, and (3) WTE technical assistance for local governments is underway. Next steps include working with municipalities to address their challenges and priorities related to waste management.



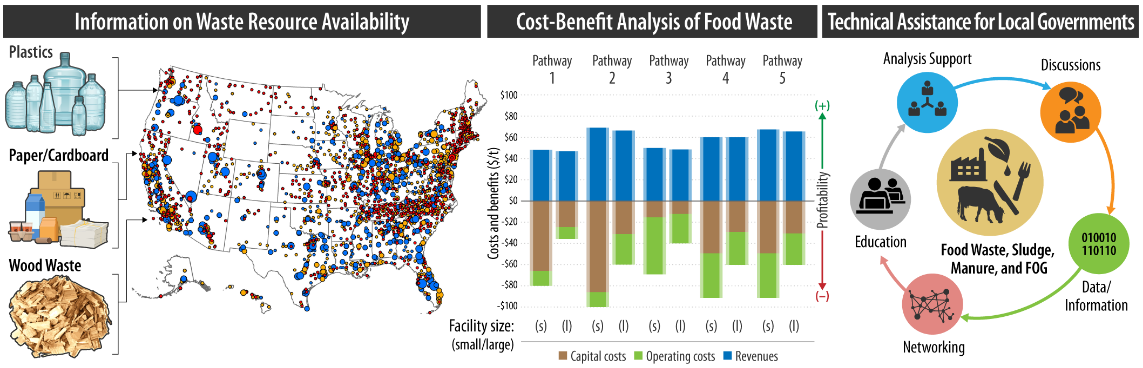


Photo courtesy of the National Renewable Energy Laboratory

COMMENTS

- I have no management concerns; the coordination with other entities appears to be very good. Working with large waste management companies for the project is critical and also seems very strong. Providing best practice guidance for others and for BETO overall with respect to working with industries like this might be helpful. Regarding approach, the first two activities (cost-benefit analysis and the collection of data regarding landfilled plastic, paper, cardboard, and wood waste) have moved forward well. I have no concerns. With respect to the WTE technical assistance activity, I was very happy to hear about the proactive approach that the principal investigators (PIs) are taking to reach the intended municipal/local/regional audiences. A clear strategy to reach entities that could really benefit from this technical assistance will be very important. I recommend trying to reach "early-adopter" municipalities that tend to be on the cutting edge that can further help pull others along. The work is exciting and poised to have a large impact, particularly within BETO. The progress and outcomes are also clear. The results seem like the type of information that will be of great interest to states and large municipalities. Overall, this is an excellent project that supports many other projects and BETO's overall goals.

- Q: Would be interested to hear more about your interaction with your industry partners. Interested to see if folks are accessing the underlying data/how they are using it. A: Have done a cross-comparison with industrial partners of their own internal partners. Have actively engaged with many industrial partners, who are looking to pull this information from the researchers and push it out to their members. Slide 24, what is small vs. large? This is a well-thought-out and necessary project. Granular-level feedstock data for many different types of organic waste. Has been making a reasonable number of presentations/publications. Have hit milestones and navigated the challenges of COVID-19 without much issue. With this kind of work regarding data and analyses, it's always about uptake and getting folks to embrace the data. I think the work around the technical assistance and getting folks to use and implement this information will be critical to (1) ensuring the work has its intended impact, (2) further refining this work, and (3) ultimately judging the success of this project. Need to spend some time/budget highlighting the work and impact that they made. Really glad that the team is planning on carrying the analysis forward into policy and actions. Certainly there are a lot of misunderstandings (if they even think about it at all) in the general public around WTE. Have spent a lot of time understanding the source of the data to use it in the correct fashion for this model. This program has made a real advancement from the quality of the data that was in this industry just a few years ago. Project appears well managed; no concerns. Actively communicating with BETO management. The approach is strong. The need over the last 5 years to more thoroughly document WTE has been largely satisfied, and this project has been a big part of addressing the need. Very proactive in reaching local/municipal governments as part of the technical advisory work. Still a bit early to judge the impact of this part of the project, but the team seems ready to dedicate the necessary effort to make this successful.

- Strengths: Good communication and integration with research partners. Clear demonstration of advancing the existing knowledge base of municipal waste (e.g., improved on known values from the U.S. Environmental Protection Agency). Able to achieve project milestone within the timeframe of the project. Providing a positive impact on national waste treatment through regional models of waste stream composition.

  Weaknesses: More information on industrial relationships would have been valuable to demonstrate clear translation of the information into value-add data for commercial application. More collaborative work with commercial partnerships would have been valuable to show limitations and challenges of various treatment facilities and how this data base could help overcome their challenges (e.g., capital expenditure [CapEx] limitations, operating expenditure limitations, contaminants of concern).

- The management plan is well thought out and includes specific areas of risk and risk mitigation. The communications plan is also good and includes regularly scheduled meetings and communication among various stakeholders. I think it is important to consider preprocessing issues, especially when looking at AD as a WTE conversion technology. There have been issues with consistency of food waste entering digestors and some negative impacts. Another area that could be considered is if the loop gets closed—for example, some communities are adding food waste to digester, but are flaring the biogas rather than using that energy beneficially. The WTE technical assistance program is very detailed and well done. The only concern is that so many communities are in budget deficit now because of COVID-19, and that the statics on recycling and reuse might not be representative.

- This project is one of several whose focus is on assessing the availability of waste resources as potential feedstocks for conversion processes. In particular, this project has mapped the availability of specific wet wastes and MSW components down to regional levels that can serve as a data base for the performance of cost-benefit analyses of various combinations of these waste feedstocks and conversion technologies. The data base and associated cost-benefit models are critical tools for helping to assess the most promising conversion technologies for a particular location and help guide where further technical development is necessary. There is no question as to the important impact this project has on waste conversion technology and BETO's goals. The project management appears to be sound, with communication among other related modeling projects and industry advisors a plus to ensure consistency and relevance. The approach presented for the cost-benefit analysis of food waste and assessment of plastic, paper, and wood waste is reasonable, though it was not entirely clear how these individual tasks fit into the bigger overall goal. Explanation of how the particular pathways analyzed were chosen would also have been helpful, along with an example of how the model works for a specific case study. Nevertheless, the results obtained are illuminating and powerful. In particular, the establishment of the WTE technical assistance program (with a well-timed public announcement of the program launch and first webinar on the same day as the presentation!) is a significant achievement. It appears that the WTE technical assistance will be a tangible way to bring the results of this project to local government stakeholders to not only make them aware of the benefits of the tools developed for optimizing their waste management, but also in providing the necessary assistance on how to use these tools. The only concern is whether the National Renewable Energy Laboratory (NREL) team will be prepared to handle the volume of work that may occur if interest in the WTE technical assistance is as strong as its potential should demand.

PI RESPONSE TO REVIEWER COMMENTS

- We thank the reviewers for their time and valuable feedback. We are glad to hear the reviewers found the WTE technical assistance valuable and a logical next step for this project. We agree and appreciate the suggestion of trying to reach "early-adopter" municipalities that tend to be on the cutting edge and can further help pull others along. The concern about whether the NREL team will be prepared to handle the large volume of work that may occur with the technical assistance is a very valid point. This is why we are adopting a phased approach so we can focus on a number of technical assistance projects that we can accomplish within a given period. We apologize that it wasn't clear how the individual tasks fit into the bigger overall goal and how the pathways for the cost-benefit analysis of food waste were chosen. The assessment of plastic, paper, and wood waste complements our work in previous years that looked at wet organic wastes (food waste; manure; sludge; and fats, oils, and greases [FOG]), and the goal is to provide a comprehensive understanding of the waste streams available for bioenergy conversions. The cost-benefit analysis of food waste ran in parallel with the cost-benefit analysis of sludge performed by our colleagues at the Pacific Northwest National Laboratory (PNNL) to better understand the cost and benefits associated with various food waste and sludge disposal and utilization options, as well as to compare the practices used today (landfilling, composting, anaerobic digestion, and incineration) to advanced biofuels production options (in this case HTL). The pathways analyzed under the cost-benefit analysis of food waste were determined in discussions with BETO management. The results of all these activities will be used to support the WTE technical assistance for local governments. We agree that limitations and challenges of various treatment facilities should be investigated in collaboration with industrial partners. However, this project does not consider treatment facilities. Wastewater treatment plants are analyzed by our colleagues at PNNL (project number 2.1.0.113). In case we misunderstood the question, the data inputs (e.g., CapEx, operating expenditures), analysis approach, and results for each pathway under the cost-benefit analysis of food waste were discussed with and reviewed by our industrial partners.

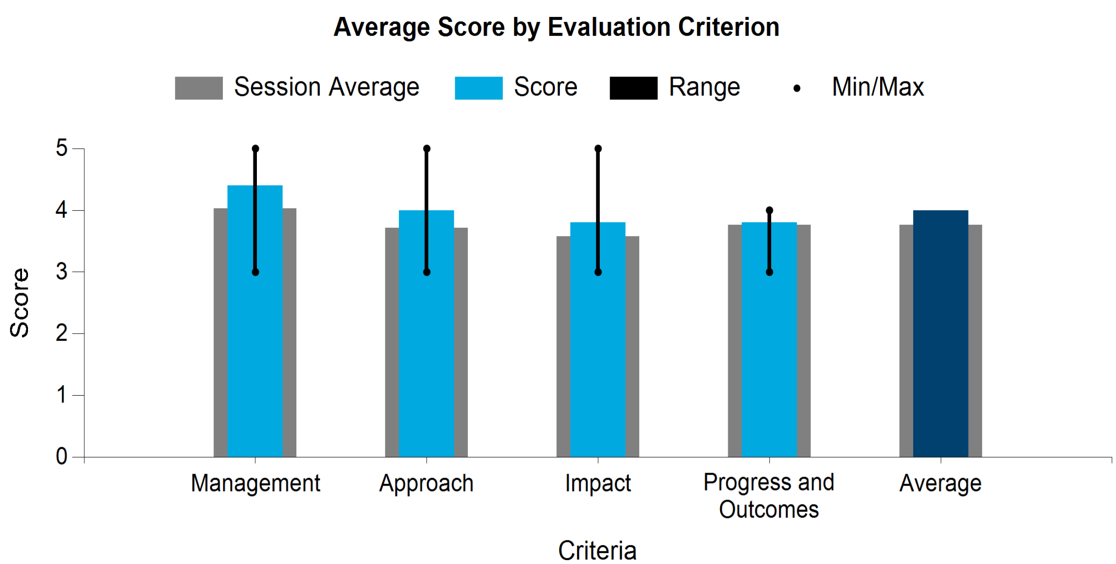
WASTE TO ENERGY: FEEDSTOCK EVALUATION AND BIOFUELS PRODUCTION POTENTIAL

Pacific Northwest National Laboratory

PROJECT DESCRIPTION

WBS:	2.1.0.113
Presenter(s):	Tim Seiple; Asanga Padmaperuma; Corinne Drennan
Project Start Date:	05/01/2015
Planned Project End Date:	09/30/2023
Total DOE Funding:	$950,000

Wet organic wastes such as municipal sludges, manures, food waste, and FOG are considered priority feedstocks for conversion to biofuels. Feedstock costs have a major impact on the feasible scale of proposed conversion and biorefining facilities and final fuel price. The BETO 2019 draft Multi-Year Program Plan establishes an MFSP target of $2.50/GGE or less for biofuels by 2030. To validate whether proposed conversion pathways can meet this target, our project will deliver and exercise a reusable, data-driven geo-economic framework to identify practical and cost-effective opportunities for pilot- to commercial-scale deployments. Despite risks from imperfect engineering, spatial, and market data, our work improves understanding of the real-world possibilities to combine feedstocks and increase plant scale to reduce the cost of biofuels. An illustrative finding from this work is that 45 regions in the United States can access ≥1,000 dry metric tons per day of feedstock at or below $50 per dry metric ton, which accounts for 82% of total wet organic wastes inventoried. Increasing modeled plant scale to 1,000 tons/day could reduce final fuel price by $0.69/GGE, compared to the previous design study scale of 100 tons/day.



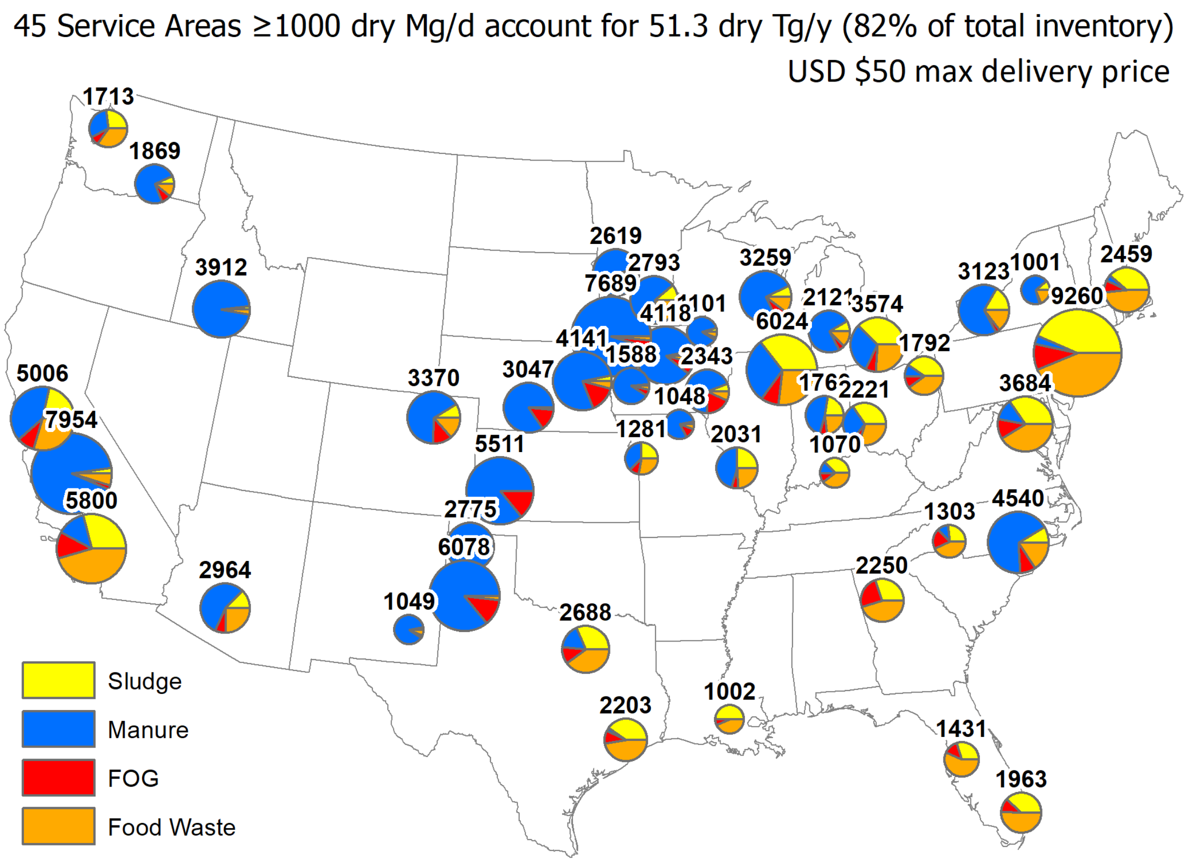


Photo courtesy of PNNL

COMMENTS

- Good progress on this project. Would like to understand how the $1 billion saving on biosolids disposal is calculated and what the disposal options used in the calculation were. Additionally, all of the conversion processes seem to have some solids remaining after energy and resource recovery. The disposal cost for those solids should be factored into the cost comparison relative to current biosolids disposal. FOG collected at WRRFs can be highly contaminated with paper and plastics and may need some type of pretreatment. FOG collected from grease traps generally is much "cleaner" in that respect. Would like to have a more detailed explanation on how percent solids and distribution of the waste streams could be controlled in full-scale operations.

- Have done significant work on the cost of logistics for biomass. Very impressive. Data visualizations are easy to understand and contain a lot of information. Well done. Clear statement about the impacts of the modeling effort. Would be excited to see the HTL technology move forward (I know this is not the goal of this work). Team seems to be interfacing and supporting other projects in the organic waste portfolio. Look to make the data and the summary information as public and accessible as possible. Perhaps something like choose your address, and the model will tell you how big you can go, as well as how big is reasonable. Seems to have navigated the challenges of COVID without much issue. Have continued to refine assumptions and update the model as data are returned. It's also good to start with the endpoint in mind. Project is a clear recognition that a single type/source of organic may not be the most advantageous way to site. Good natural extension of the work that was previously done on feedstock availability/location. Will the logistics models also have an element that looks at emissions/greenhouse gas impact? Spend a lot of time understanding confounding factors in their waste—for example, percent water impact on hauling costs. Model is more of a feedstock supply model, so it's agnostic to the conversion technology. Model seems to handle many common challenges and impacts, like landfill bans.

- I have no management concerns; the coordination with other entities appears to be very good. The approach appears to be logical, stepwise, and builds on prior work. The incorporation of high-strength waste will also be very important, particularly on a smaller spatial scale. The answer to the reviewer question regarding stakeholder engagement was very good and provides confidence regarding input data quality. The work is poised to have a large impact, though currently focused within the national lab network. Dissemination will be very important for a larger national impact. Plans appear to be in place to move in that direction, but strengthening the push from information sharing to having others outside of the national lab network start to use the data will be an important step. The progress and outcomes are clear. The ability to incorporate different technologies and different cost assumptions make the work very flexible. The ability to remove the $0 cost assumption is good. Again, the results seem like the type of information that will be of great interest to states (from a legislative perspective) and large municipalities (from a management perspective). I encourage the PIs to proactively approach dissemination goals to reach the largest and most impactful audience possible. Overall, this is an excellent project that supports many other projects and BETO's overall goals.

- Strengths: Effective inter-lab communication through the project. Invested valuable time to communicate with wastewater treatment plants and waste haulers for validation and clarification of the data. Geographic modeling of feedstock price vs. distance to haul appears to be a valuable approach in aligning with real-world application. Economic modeling for value-add bio-commodity production will bring positive impact to regional communities.

  Weaknesses: Appear to still have work to do in clarifying market pricing for feedstock over time (e.g., relationship between purchase price and feedstock quality, feedstock competition due to value-add end market products). No greenhouse gas calculations provided (due to early stage of data collection). The 2022 review would benefit from a presentation of this modeling. Demonstrating more details around the value creation from bio-commodity production within this work would have been valuable to review in order to confirm true economic and waste management benefits.

- This is another project that is focused on assessing availability of wet waste as a feedstock for conversion to liquid biofuels. The model being developed in this project evaluates waste sources over a defined localized region, along with transport costs and other relevant input variables to help determine cost-effective quantities and compositions of waste available in a given location (referred to as a hot spot) and the expected biocrude yield. This model is an important tool for identifying the most competitive and sustainable locations for biorefineries, and its impact is clearly significant. Though the model is said to be conversion-technology-agnostic, the examples provided and discussion presented all assume use of HTL for production of biocrude. This is understandable, given that the PNNL-based modeling team works closely with the experimental team at PNNL, which is known for its HTL research work. The cross-project integration between the modeling team in this project with the HTL experimental team and TEA team (represented by other presentations in this session) is an excellent structure for project management, where each team takes data from the other members and feeds results from its focus work back to the other team members to drive overall progress. The approach presented was informative and reasonable, with good use of examples to show how the model works and what its current capabilities are. Results to date are encouraging, with all current milestones met. However, the claim made that regional blending can achieve a 10x increase in HTL scale and a corresponding reduction in the MFSP by $0.69/GGE is a bit misleading. The basis of the claim appears to be that certain regions can supply the needed waste volume (as blends) that would, in theory, support the 10x increase in size, but this does not mean that the proposed 10x scale-up in size (equal to 1,000 dry tons of feed per day) will actually be achievable from an operations perspective, especially given that the current HTL scale being demonstrated is only in the range of 2–4 dry tons/day. Thus, the associated drop in

MFSP has not really been validated. Also, there are still some assumptions in the model (e.g., omission of tipping fees) that question the overall accuracy of the predicted results, though the project team acknowledges these and has stated that there is a plan to gradually make the necessary refinements as further model development occurs in the project.

PI RESPONSE TO REVIEWER COMMENTS

- General comment responses: We thank the reviewers for their time and effort. The Peer Review process is our best opportunity to receive critical external reviews on the project. Your feedback helps us to focus our research, strengthen our methods, and make important connections. To summarize the overall project and context for current work, we previously focused on assessing the quality and quantity of priority wet organic wastes, including sludge, manure, food waste, and FOG. Next, we assessed economically sustainable sludge and manure feedstocks on an individual basis to estimate the minimum feasible deployment scale of stand-alone HTL for wastewater treatment facilities and large confined animal operations. We are now in the process of quantifying cost-effective regionally optimized feedstock blending to help increase the potential number and scale of a national network of integrated conversion and biorefining facilities. We are just now entering the third quarter of our first year in the current project phase. The following milestones define the remainder of the project: (Q1) integrate multimodal transportation network and multi-objective optimization to balance feedstock transport costs with plant scale (12/31/2020, complete), (Q2) characterize high-strength organic waste sources not already inventoried (3/31/2020, complete), (Q3) integrate comprehensive feedstock pricing into aggregation and siting model (6/30/2020), (Q4) quantify cost-constrained regional feedstocks using enhanced feedstock model (9/30/2021), (FY 2022) economic blending analysis (9/30/2022), and (FY 2023) finalize biorefinery siting and sensitivity analysis (9/30/2023).

  We are pleased to know the value of our project was clearly demonstrated in the presentation. It is our hope that our flexible, technology-agnostic, geographically explicit feedstock supply and biorefinery siting model will be used to build an evidence-based business case for industry partners to move forward with HTL and other transformational technologies.

- Scoring criteria specific comment responses:

- Management: We are pleased the reviewers recognized the value in our agile cross-team, cross-lab management approach.

- Approach: Modeling greenhouse gases is not explicitly within our scope, and other projects are focusing closely on this topic. Specifically, Argonne National Laboratory's Supply Chain Sustainability Analysis project applies their Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model to PNNL-developed conversion life cycle process models. The resulting greenhouse gas accounting is published in the Supply Chain Sustainability Analysis report, which includes analyses for all BETO technology pathways and coincides with the state-of-technology (SOT) reports, including PNNL's HTL SOT. However, it is likely we will be asked to supplement Argonne's greenhouse gas accounting with emissions estimates from transporting wet organic wastes to the conversion/biorefining facility.

  Thus far we have not considered scum collected at wastewater treatment facilities. However, we are in the process of modeling scum based on influent flow to include in our National Wet Waste Inventory. As one reviewer mentioned, wastewater scum could be contaminated with paper and plastics. However, this should not pose a technical challenge for HTL reactors. We will be sure to incorporate any additional formatting costs to handle this feedstock depending on the conversion technology being modeled.

  Regarding the question of how "percent solids and distribution of the waste streams could be controlled in full-scale operations," we anticipate that biorefineries will function similar to petroleum refineries in terms of trying to maximize fuel production in light of dynamic changes in feedstock quantity and quality, but we hope to minimize daily to weekly variability through optimization. The resource assessment phase of this project focused on identifying sustainable supplies of wet organic waste streams. Commodities with infrequent or highly variable flows or existing high reuse demand were not included. The flow of municipal wastewater solids, confined animal manures, food waste, and target FOG components have very steady long-term supply behavior. Most variability in the quantity of these waste streams comes from slow regulatory changes. If anything, more stringent regulation will increase the feedstock magnitudes through increased capture or diversion requirements, which will also increase traditional management costs, thereby improving conversion economics. As we move into the economic, regionally optimized blending phase of the project, we will experiment with different waste blending model control options during optimization. For example, (1) annual waste volumes will be assessed on an hourly to daily basis to determine hauling frequency for a given source, (2) regulated wastes could be given priority over unregulated wastes, (3) we will investigate different waste aggregation strategies (separated vs. mixed-waste pickup), and (4) different objective functions will be applied to maximize either feedstock utilization or conversion efficiency. We will develop a range of realistic blending scenarios that represent the flexible approaches likely to occur in different regions of the United States.

- Impact: We agree that retiring the $0 cost assumption is a significant outcome of this work. We acknowledge that transportation cost is an incomplete representation of total feedstock price. In FY 2021 Q3, we plan to expand the notion of feedstock price to include additional cost and savings elements such as market pricing (competitive feedstock use), service (tipping) fees, avoided costs, and credits. This will be an ongoing process and will require input from DOE, industry, and the techno-economic modeling teams. Although we possess detailed tipping fee data, we made the decision to initially omit tipping fees because we were interested in first understanding the impact of delivery costs on cost-effective feedstock before layering in other cost elements. Omitting tipping fees should not jeopardize the accuracy of the current estimates. If anything, the current results are more conservative, as applying tipping fees will offset feedstock transportation costs.

- Progress and outcomes: Several reviewers commented on the need to deliberately disseminate results, particularly to state legislators and large municipality managers. We plan to actively share results in mid-2022 after we have had a chance to finalize the feedstock model and perform quality control on the results in preparation for integrating our results into the FY 2022 SOT report for HTL. We plan to work with our graphics team to package the data and findings into standardized, easy-to-consume downloadable infographics. The underlying data will also be submitted as a Mendeley *Data in Brief*, which will allow others to quickly access and cite the data. As our model matures, we will extract metrics that better characterize the overall value of siting scenarios.

  The reference to $1 billion in potential savings from avoided municipal biosolids disposal was reported as a finding in the *Journal of Environmental Management* (https://doi.org/10.1016/j.jenvman.2020.110852). The estimate represents the difference between biosolids disposal costs for the "Baseline" and "HTL Max" scenarios listed in Table 5. Essentially, the HTL Max scenario summarizes the impacts of building new HTL reactors everywhere that they are modeled to be cost-effective (i.e., net present value = 0), which was reported to be any wastewater plant influent flow of 4.6 million gallons per day. The total reported savings potential ($1.43 billion/year) in Table 5 accounts for some minor savings from existing non-HTL solids reduction strategies in the hypothetical composite fleet. However, the underlying data for Table 4 indicate that the 1,161 economic HTL projects alone can also reduce biosolids disposal costs by >$1 billion/year compared to current practice. This analysis did account for the disposal costs of HTL residuals and wastewater. HTL wastewater treatment costs were adopted from Snowden-Swan et al. (https://doi.org/10.2172/1415710). For all solids disposal endpoints, regardless of technology, the model assumed an average disposal cost of $400/dry short ton, which included formatting, dewatering, hauling, tipping, and indirect expenses. The same value was used to estimate savings from avoided disposal.

It was not our intention to mislead the reviewers with respect to the claim that blending wet organic wastes could improve plant scales by a factor of 10. The reviewer is correct; the projected MFSP has not been validated in the commercial sector. In fact, if it had, we would not need to model it. The purpose of the national model exercise was to inform other teams, such as the TEA/SOT team, with a preliminary sense of the number and potential size of biorefineries in the United States, such that they could design a blending sensitivity case to supplement the SOT. We plan to spend the entire next 2 years refining and calibrating the biorefining siting analysis. Even then, these results are merely our best projections of what is possible in the real world.

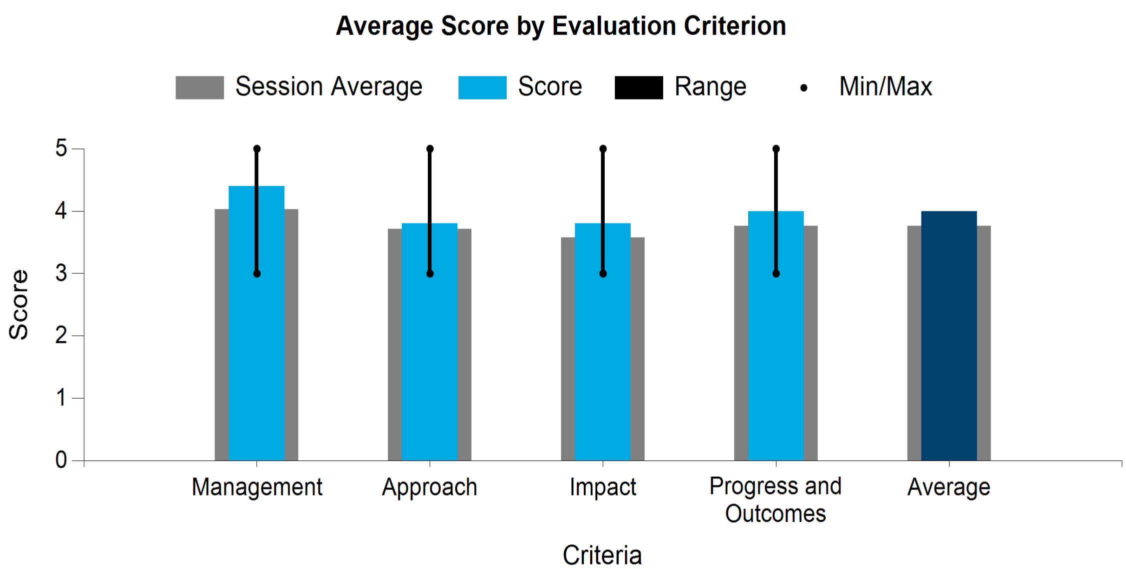
ANALYSIS AND SUSTAINABILITY INTERFACE

Pacific Northwest National Laboratory

PROJECT DESCRIPTION

WBS:	2.1.0.301
Presenter(s):	Lesley Snowden-Swan; Asanga Padmaperuma; Corinne Drennan
Project Start Date:	10/01/2016
Planned Project End Date:	09/30/2022
Total DOE Funding:	$1,500,000

This project provides technical, economic, and sustainability analysis support for several biomass conversion routes to hydrocarbon fuels and chemicals. In the context of the Organic Waste area, this presentation focuses on the project's wet-waste HTL task. Building on previous wood and algae work, PNNL began testing and TEA of wet-waste HTL and biocrude upgrading in FY 2016. The design case projecting the 2022 cost target for the pathway was published in 2017, and annual SOT assessments were conducted since then to guide the research and track the performance and modeled MFSP toward the technical and cost goals. Data availability, a common challenge for TEA, is mitigated by frequent interaction with researchers to exchange information and review sustainable cost-reduction strategies. Through the integrated experimental/analysis project efforts, the SOT MFSP was reduced from $7.16/GGE to $4.50/GGE, and planned research will enable BETO's 2022 ($3/GGE) and 2030 ($2.5/GGE) cost targets. In addition, uncertainty quantification using a reduced-order model approach was performed and indicates a −25% to +39% uncertainty around the SOT biocrude selling price. As part of this effort, a predictive HTL yield model based on continuous system testing of 15 waste feedstocks in PNNL's process development unit (PDU) was developed, the first of its kind in the literature.



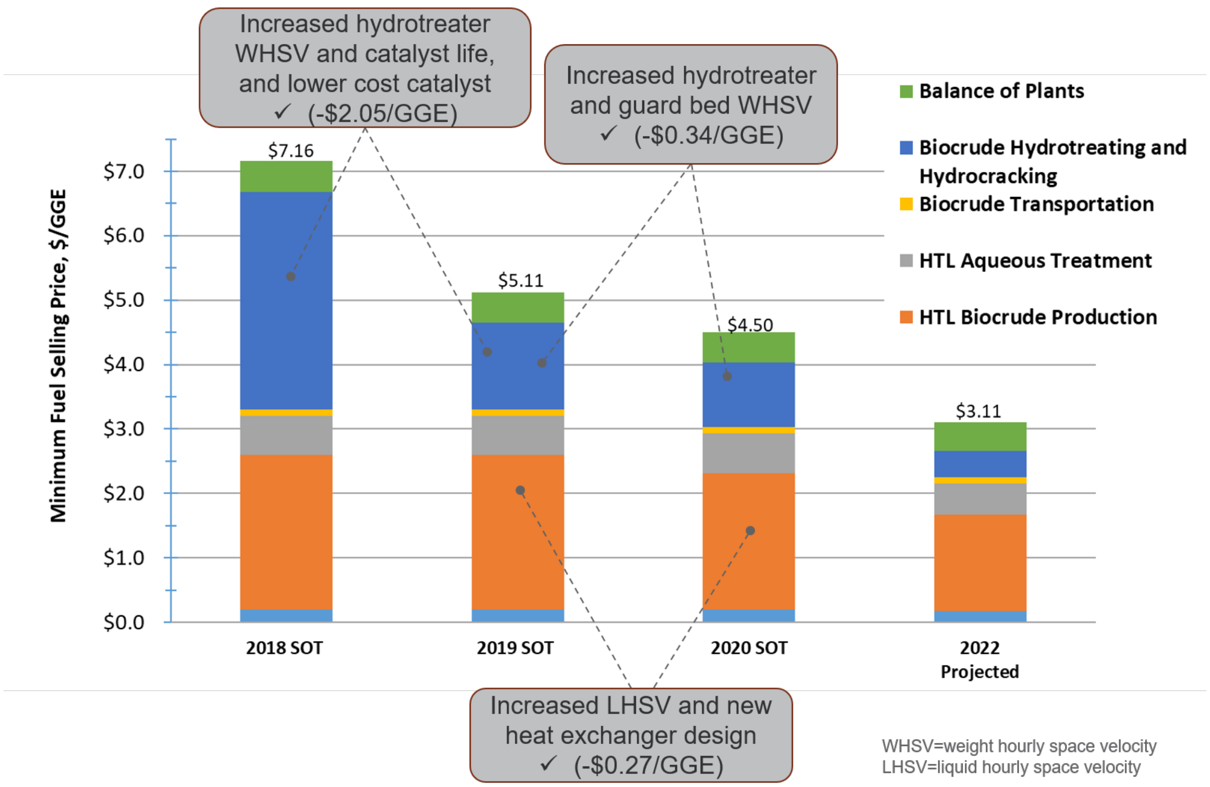


Photo courtesy of PNNL

COMMENTS

- Slide 9 model needs to account for the lack of the bio-intermediate rule if transporting biocrude. Good use of value engineering to reduce the capital costs of the system 13% and to incorporate the results of this project into the TEA. Clear lines of communication, and involvement in other projects that are likely to influence the MFSP. Project seems well presented. Modelers are making significant effort to present work and get out and meet practitioners and laboratory personnel at conferences and in their labs (as appropriate during COVID). Material costs have escalated rapidly and might offset some of the gains around capital costs. Although all projects would be largely equally impacted. The team has hit its annual milestones to publish an updated SOT and is on track to publish their business case. That publication should embrace graphics and a simplified abstract to reach a broader audience. Waste is an inevitable part of economic activities, but it is also a great opportunity for biofuel production. This could help change the conversation from landfilling and incineration to valorizing these cost centers. Would be good to see citations/earned media. This would be a good record of how folks are taking up the analysis. The work is clearly helping to drive research elsewhere in the WTE portfolio by focusing on some of the most critical and impactful elements of WTE. Material costs have dramatically escalated in 2020; is the sensitivity to this captured in the analysis in any way?

- Strengths: Clear demonstration of strong relationships within experimental team and good wastewater treatment partnerships for validation of progress. Already demonstrated MFSP of <$2.5/GGE for Detroit case study, validating the clear impact of this project to regional communities. Identified key feedstock impacts on process efficiency (e.g., relationship between FOG content and reduced MFSP). Strong knowledge of local and federal incentive plans for incorporation into regional modeling (e.g., renewable fuels credits).

Weaknesses: Further information on what has been learned from partnerships/engagements with commercial partners would have been valuable, including what insights had influenced your experimental decisions. It was unclear whether fractionation/product purification was incorporated into scope. This will be critical for final GGE price. Unclear if carbon in the aqueous phase and its potential cost for disposal was being considered in the model. More information on the projected capital investment relative to the research findings would have been valuable for validation of commercial viability (e.g., expected payback period on a given plant size, key cost drivers for the technology integration).

- The project seems to be very well managed. It is well integrated with other national lab projects in particular. Some of the findings regarding the ability/viability of scaling up HTL to 1,000 dry tons/day seem disconnected from actual data, given that operation at this kind of scale, including the large quantities of waste generated that need to be dealt with, has not been demonstrated. The HTL aqueous waste stream is included in the TEA/life cycle assessment (LCA), but it seems to be in early stages and the assumptions made regarding treatment needs were not clear. This is a very important part of the scale-up and delivery of the technology, and I encourage the team and BETO to focus on this area. The project has very nice impacts with respect to stimulating research in areas that will have the greatest impact on decreasing the cost of HTL.
- This is the third of three integrated PNNL projects that leverage each other to accelerate development of HTL for production of liquid fuels from wet wastes. This project addresses deployment and refinement of the TEA model to identify key variables that drive cost for the experimental team to explore, with the experimental results feeding back into improving the accuracy of the TEA. The management structure that incorporates this feedback loop among the PNNL teams is highly commendable and appears to be working well based on some of the results presented. While it is understood that this HTL TEA project falls under the scope of a much larger analysis project, it would make more sense if the experimental and TEA work were combined into a single project, as is the case for the other projects in this Organic Waste session. The project approach is straightforward and sound. The results show a significant decrease in the predicted MFSP for the liquid fuel product over the past several years, which is consistent with BETO's goals and desired outcomes. The impact on HTL development and for BETO is therefore considerable. Although feedstock price variation is now explored in the sensitivity analysis, the continued use of zero feedstock cost as the base case still appears unrealistic. A more representative cost should be determined and used for the base case and then sensitivity performed on that. With respect to results, some results are a bit confusing due to limited details provided. For example, it is not obvious how the improved heat exchanger setup that uses three heat exchanger units instead on one unit previously and two pumps instead of one has a lower capital cost. It is also not clear how carbon and nitrogen removal in the aqueous product phase will be improved, and whether this is included in the sensitivity analysis. While the primary drivers for MFSP reduction from 2018 through 2020 are identified, it is not clear what is responsible for the 2022 projected value, which is significant because it is close to achieving the BETO target. Nevertheless, the overall results are encouraging, and the project is meeting its milestones and generally appears to be on track to guide further HTL development.
- This project is meeting all goals and milestones. Results to date are very encouraging. Being able to use FOG in this process is a benefit to the water sector. Need to see a detailed mass balance. Also, there needs to be a description of any waste materials from this process and disposal options/issues. Also, there should be more information about any recycle streams to the WRRF and their impact on nutrient removal, permit considerations, etc.

PI RESPONSE TO REVIEWER COMMENTS

- We appreciate the time spent by the reviewers and for their insightful comments and feedback. Response to 1st reviewer: We agree that there currently isn't an avenue to track credits associated with the intermediate biocrude ("bio-intermediate") between an HTL and upgrading facility under the current

Renewable Fuel Standard. However, the U.S. Environmental Protection Agency proposed a rule change to the Renewable Fuel Standard in October 2016 that would allow for bio-intermediates, and our hope is that as the technology advances toward industry adoption, this rule will be fully promulgated in the future. We do agree with the reviewers to include simplified figures in publications so the general public will get a better understanding. The national laboratories are implementing a new tracking system to collect alt metrics, which is in line with the comments made by the panel. Regarding rising material costs, all costs for the state-of-technology assessment are presented in 2016 dollars for consistency with other BETO pathway analyses. Costs for BETO analyses are due to be updated to a more recent year and will indeed reflect the escalated material costs that you mention. We did not include sensitivity around cost year in the analysis but will consider including this in the future.

- Response to the 2nd reviewer: Thank you for highlighting the value of working with industrial partners. This project relies heavily on the input we receive from our partners; specifically, during the development of the design case (2017), we asked for industry review and received up to 500 comments that influenced the flowsheet modeling and experimental work to follow. The issue of nitrogen loading in the HTL aqueous can create a bottleneck in secondary treatment and challenge discharge permits. This led to researching pretreatment options. Industry feedback about total metals concentration in the biocrude and the limits of commercial hydrotreaters directed our use and development of guard beds and now advanced biocrude pretreatment. Working with partners revealed that color bodies in the recycled aqueous phase could impact ultraviolet disinfection, even at high dilution rates, and drove a focus on identifying and removing color bodies. These are three of many examples.

  We regret that under time constraints we were not able to present as much detail on the process model as we would have liked. The model includes final product separation (distillation) into blendstock fractions (diesel, naphtha, jet), and all capital and operating costs for this step are included in the MFSP. The HTL aqueous phase is currently modeled to be treated with ammonia stripping and then recycled back to the wastewater treatment plant headworks. We are working with the industry to better understand the possible limitations with this option and testing alternative options in the laboratory, including anaerobic digestion/annamox and thermo-catalytic conversion methods, and will be incorporating updates into the flowsheet as we identify the most promising option.

  Projected capital investment is estimated based on the key parameters derived from the research; however, capital costing is modeled for an "n^{th} plant" and therefore will be significantly lower than the first few plants that are built. Payback period is indeed another economic metric rather than MFSP that could be presented (assuming market values for biocrude and final fuel blendstock). We will consider including this metric as sensitivity to MFSP in the future.

- Response to the 3rd reviewer: Thank you for your point regarding presenting the detailed mass balance. In future reviews, we will give more detail around the process flowsheet and description of waste streams from the process and associated challenges. The collective team is actively working with the industry to better understand the potential impacts that recycling the HTL aqueous stream will have on a WRRF's operations such as added ammonia and organic nitrogen and the presence of color bodies. More beneficial options for the HTL solids/ash other than landfill disposal are under consideration.

- Response to the 4th reviewer: The alternative scenario considering a 1,000-dry-ton/day regional wet-waste processing plant is based on PNNL's HTL testing of a waste blend representative of an actual urban area (Detroit) and geospatial analysis of the nation's wet-waste sites (see WBS# 2.1.0.113), and is being considered to investigate and illustrate to external stakeholders the potential economic benefit and environmental impact of transporting wet waste to achieve economies of scale. Absolutely, there are logistical challenges of hauling waste around; however, much is already being transported today, as in the case of food waste and FOG being co-digested at WRRFs and manure being trucked many miles across counties/states given land application limits. We are therefore considering this type of scenario in the realm of possibilities moving forward.

The baseline assumption is that the HTL aqueous phase is treated by ammonia stripping and then recycled back to the WRRF. Indeed, effective treatment of the aqueous phase is critical to the successful scale-up of the HTL technology, and we continue to work on testing of industrially available and novel treatment/valorization methods in our PDU project to drive toward the most economical and environmentally beneficial solution.

- Response to the 5th reviewer: The zero feedstock cost assumed for the base case is considered to be conservative given that it is likely there will be some sort of “tipping fee” that a WRRF would pay an HTL plant owner/operator. However, we are modeling a future time where it is entirely possible that waste for renewables production could become a commodity due to increased demand (e.g., the recent shift in FOG demand for hydroprocessed esters and fatty acids production).

  We regret that time constraints did not allow for more explanation of the detailed heat exchanger analysis. To clarify, although there are two additional heat exchangers, the material usage is much lower with the new design, primarily because the design pressure (and thus wall thickness) is lower on all of the shells (~200-psia heat transfer oil vs. 3,000-psia HTL reactor effluent for previous design) and the tubes for the first 500°F of surface area needed for heating.

  The base case for the design assumes ammonia stripping. The model shows that the stripping process removes approximately all of the ammonia nitrogen, 60% of the total nitrogen, and 54% of the carbon. However, testing of ammonia stripping is needed to validate the model. Also, testing of alternative strategies is being conducted on the PDU project to drive toward the best solution for the aqueous phase. A sensitivity analysis was conducted on the aqueous-phase technologies tested to date, included in the PDU project review, and published in the 2020 SOT report. From the preliminary data, it is estimated that the thermochemical methods tested thus far could add $0.57–$0.74/GGE and $0.08–$0.14/GGE to the SOT for high and medium chemical oxygen demand (COD) removal methods, respectively. Removal of nitrogen species is estimated at 80%–100% for ammonia and 0%–100% for organic nitrogen.

  The target parameters for the 2022 projected case include increased HTL solids content and biocrude yields, decreased HTL heat exchanger capital cost, and increased biocrude hydrotreating catalyst performance.

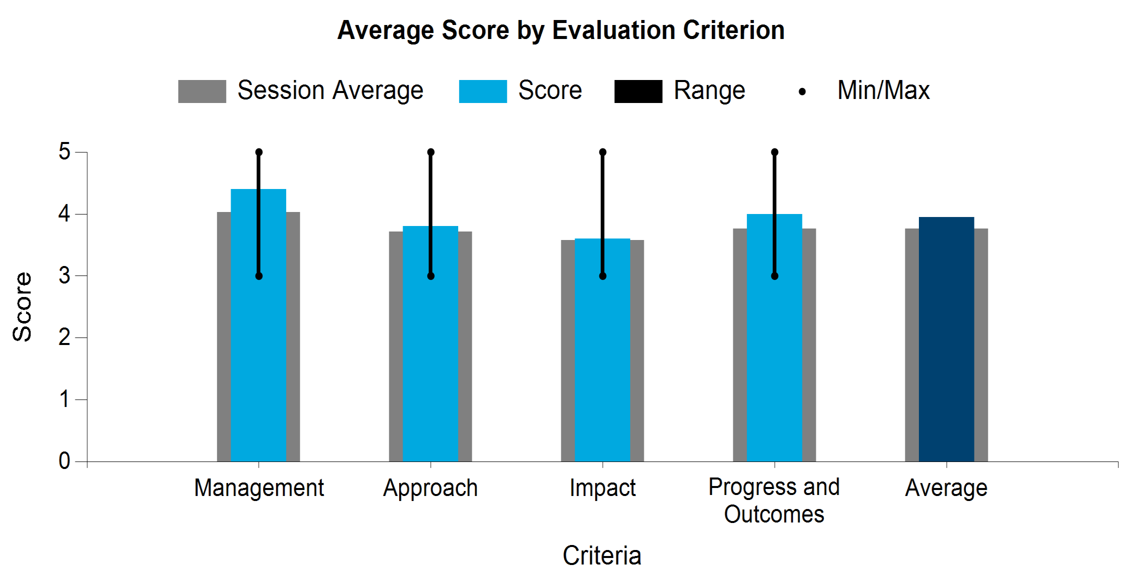
BENCH-SCALE HTL OF WET WASTES

Pacific Northwest National Laboratory

PROJECT DESCRIPTION

WBS:	2.2.2.302
Presenter(s):	Michael Thorson; Asanga Padmaperuma; Corinne Drennan
Project Start Date:	10/01/2018
Planned Project End Date:	09/30/2022
Total DOE Funding:	$1,080,000

This project is advancing the state of technology for HTL to make it an economically viable pathway to convert wet wastes (existing liabilities) into high-cetane diesel blendstocks. This project addresses two key roadblocks to commercialization: (1) the cost of capital for HTL and (2) hydrotreating catalyst activity and life. We have improved catalyst performance by using a commercially relevant NiMo catalyst, which enabled a 3x increase in catalyst activity to achieve industrially relevant reaction rates (weight hourly space velocity 1.0 h^{-1}). Catalyst and guard-bed developments have enabled significant improvement, thereby setting us to meet the 2022 project goal of 2,000 hours of stable hydrotreating at a weight hourly space velocity of 0.75 h^{-1}. This project is evaluating the use of regional wet-waste blends and increased solids content to reduce HTL capital costs on a per-unit biocrude basis. Testing with regional wet-waste blends of food, sewage sludge, and FOG has indicated no negative effects on biocrude quality or HTL performance, demonstrating the viability of larger, regional wet-waste HTL plants. Increasing the solids content of the feedstock has resulted in increased process yields and enables further HTL process intensification. By focusing on the highest-impact research, this project is projected to meet or exceed the modeled costs targets set by BETO. The technical advancements made in this work can be used by industry to reduce HTL costs, de-risk piloting, and commercialize HTL technology.



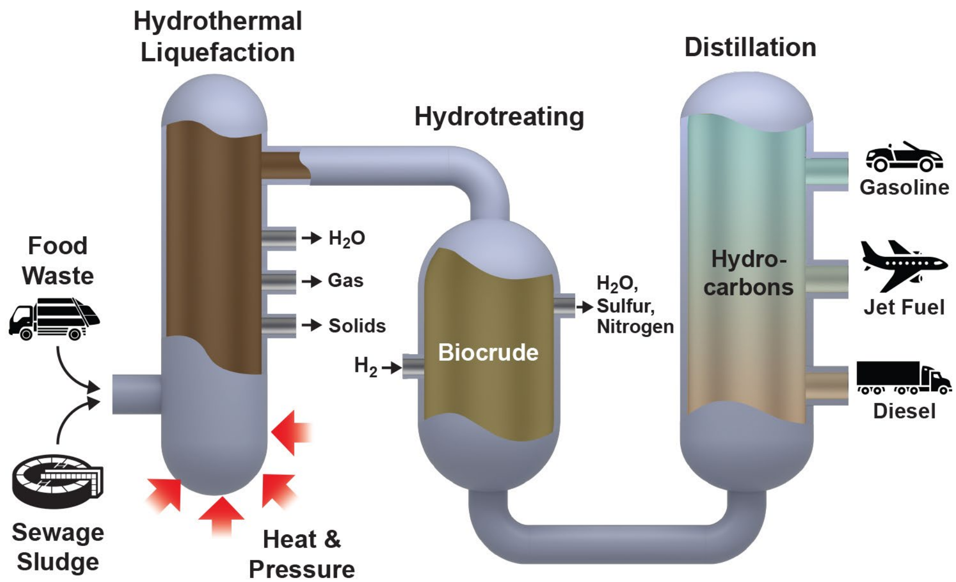


Photo courtesy of PNNL

COMMENTS

- Should look at resilience of the process to variability. It's unlikely that blends will be fed exactly at the defined ratio. For instance, as food waste is dumped in the feed hopper, the percent is likely to vary within a range. Showing if and how this impacts performance would be very interesting. It would also make clear whether fine control of materials is critical or whether there is a lot of tolerance. My hypothesis would be the latter, because of how resilient HTL is. This becomes a big selling point in that the process can be adjusted in real time by an operator. In a process that is as close to commercial as HTL is, understanding the level of process control/tolerance is critical to transitioning process management from scientists to technicians. Clear focus on the elements that reduce the MFSP of HTL-derived fuel. Goals are specific, measurable, achievable, relevant, and timely (SMART), and clearly sequenced to a larger overarching goal. Clear and frequent communication with DOE and other projects on HTL fuels. Coordinating widely. Using the work of WBS 2.1.0.113 to help with selecting the right feedstock blend. HTL needs to be commercially demonstrated. "Perfect" is becoming the element of "good enough" to be commercially successful. Would be ideal to get an actual unit operating in the field. Not meant to criticize effort, since I know the team is working on these issues (and has been for many years). Have clearly broken down the large factors that address final selling price of the product, and are clearly driving toward the goal of reducing cost on each of these. It is clear that progress is being made in line with the overarching BETO goals on this project. Have been constantly mapping the work at the bench scale to the engineering scale to confirm that data are applicable at larger scales. Well presented. Knowledgeable and concise presenter.

- Strengths: Demonstrated value-add relationships outside of academic and research institutions (including refineries, wastewater treatment companies, and energy agencies). Suitable scale-up plan for technology validation and confirmation of commercial viability—valuable advancement in catalyst life and operational performance in HTL application.

  Weaknesses: More information around trace components and their impact over time on operation, as well as pre-feed requirements to prevent performance reduction, would have been valuable in this review. It was difficult to determine what was in scope with regard to the HTL development work. It would have been valuable to review the boundary limits of the project in order to understand what was out of scope (e.g., product purification for industrial validation). Heat exchanger design evolution did not appear to have strong enough merit to warrant it being national lab scope of work. More appropriate to be outsourced to an engineering design firm.

- The project has had some successful outcomes and has identified various risks and risk mitigation. The project is well managed and is on schedule relative to the projected milestones. Although there are pumps that can pump high-solids-content wastewater sludge, sludge has rheological properties, especially in that solids range, that could be impacted by pumping. It usually results in a change of viscosity. It would be important to understand the sensitivity of the HTL unit and if it is affected by viscosity changes. I would like to see a mass balance to understand any issues with disposal of solids from this process and any recycle stream to the WRRF. The concern is the quality of waste solids that are produced, their characteristics, and options for disposal or beneficial use.

- The project seems to be very well coordinated with other national lab projects and with industry. Management appears to be excellent. With respect to the approach, the overlap with the HTL PDU is a bit unclear. It is unclear how this project works with the PDU to verify consistent results with similar feedstocks, similar waste streams, etc. The upcoming work on blends including manure will be useful for understanding the trade-offs of different feedstocks from the proposed regional blends. The ability to use high-solids blends appears to be very good, and the polyethylene terephthalate (PET) results are exciting. Work focused on extending catalyst lifetime will be important; it is not clear what the approach to actually extending the catalyst lifetime is. A guard-bed reactor was mentioned but not elaborated on. It is unclear whether this is part of that effort. Research on the liability/utility of waste/byproduct streams will be important to pursue. This seems like a very important area if this technology is to be widely utilized, particularly at the large regional scale that is being discussed. As with other projects, dissemination and outreach seems to be critical. Overall a very good project that is moving the HTL technology forward.

- This project reports on experimental work at PNNL in HTL on various aspects that are intended to improve knowledge and reduce barriers to commercialization of this technology. PNNL has been one of the leaders in cutting-edge research on HTL and in supporting efforts for commercialization, and it is encouraging to see this work continue in this project. The close working relationship between this experimental team, the feedstock analysis team, and the TEA team, as embodied in the management and illustrated by good examples in the approach, is a highly effective and efficient way to drive rapid and meaningful development of HTL technology. This project structure is also helping to steadily reduce the cost of liquid fuel products, which directly supports BETO's objectives. As a water-based technology, HTL is a cost-effective method for converting wet wastes to liquid fuels by avoiding the significant costs associated with drying the feed. The specific progress shown in the experimental results from increasing feed solids content and in increasing hydrotreater catalyst activity represents important achievements and supports the associated reduction in overall fuel cost. The results of blended feed tests are also important and encouraging from a performance perspective, though it is not clear that they support the claimed order-of-magnitude increase in HTL plant size and associated decrease in fuel price. Just because there is sufficient feed quantity in a regional location (represented by the tested feed composition) to allow operation at an increased scale does not necessarily mean that a plant at that scale can be successfully operated. This credit can only be truly claimed when HTL is successfully demonstrated at the specified scale, or at least when justification can be made that scale-up to the desired size is feasible based on current or previous successful scale-ups. Nevertheless, experimental work in key areas identified by modeling is critical to further development of HTL technology. In particular, incorporation of plastics into blended feedstocks (the presentation briefly stated that HTL of polyethylene terephthalate plastic has promising results, but none were provided) would represent another important achievement and allow more flexibility in available feed types.

PI RESPONSE TO REVIEWER COMMENTS

- We would like to thank the reviewers for their thoughtful and constructive comments and questions. We appreciate the positive feedback regarding our progress, successful outcomes, project and risk management, and impact in the community and toward commercialization. We will address key questions and areas that need further clarification.
- "Important to understand the sensitivity of the HTL unit and if it is affected by viscosity changes," "Should look at the resilience of the process to variability," and need "pre-feed requirements to prevent performance reduction." Yes, sludge rheology and viscosity data are critical to solids handling, pumping, plugging, and sustainable operation. We have found that the rheology of wet-waste feedstock is significantly influenced by several factors, including the composition of the feedstock, the solids content, and the ash. We have processed dozens of real-world feedstocks in our continuous flow reactors. In general, the simplicity of the HTL process makes it well suited to handle variations in feedstocks with the appropriate grinding, homogenizing, and/or shredding. The ash content, the fat content, and the size of large particles (e.g., rocks and straw) have some of the strongest influences on the processability of the feeds. The PDU project (sister project) does a lot of work looking at feedstock rheology, feedstock processing, and understanding its impact on HTL.
- "Understand any issues with the disposal of solids…and any recycle stream to the WRRF" and "Liability/utility of waste/byproduct streams will be important." We agree that the disposal or treatment strategy for full-scale integration within a WRRF is needed for the HTL aqueous and solids streams. PNNL is developing multiple promising commercially viable treatment solutions for the aqueous streams, including catalytic hydrothermal gasification, anaerobic digestion, wet air oxidation, and other processes to clean up the stream. The ultimate goal is for all or part of the aqueous stream to be recycled to the headworks of a WRRF. Although the solids stream may meet landfill or land application specifications, we believe there is an opportunity to improve the overall process yield by extracting residual oil from the solids stream.
- "Overlap with the HTL PDU is a bit unclear." The PDU is a much larger project that tackles many of the key challenges for scale-up and implementation of HTL. We interact and leverage the work done on the PDU project. For example, we will leverage work done on the hydrotreater guard bed as we look to demonstrate 2,000 hours of hydrotreater performance in FY 2022. Also, we will leverage the technologies that they develop for aqueous treatment to advance the state of technology. On this project, we are focused on implementing and developing technology that drives the MFSP down in our SOT. This includes things like extending hydrotreater catalyst lifetime and activity and quantifying the yield and process performance associated with processing higher-solids-content feedstocks. The PDU scales this work up the engineering-scale system.
- "I would like to see a mass balance." We agree wholeheartedly that a mass balance is a critical tool for process development, evaluating and understanding processes, and identifying improvement opportunities. In an earlier version of the peer-review slides, we included a Sankey diagram for both the overall mass balance and the carbon balance, but we left them out due to the limited presentation time. Overall, a typical dry, ash-free yield for an HTL experiment from sewage sludge is approximately 41% biocrude, 33% aqueous, 19% gas, and 7% solids. On a carbon basis, a typical overall yield for an HTL experiment is approximately 58% biocrude, 24% aqueous, 10% solids, and 8% gas.
- "It is not clear what the approach to actually extending the catalyst lifetime is" and "A guard-bed reactor was mentioned but not elaborated on." To extend the hydrotreater catalyst life, we will use a guard bed to remove the Fe and other metals (hydrodemetallization) from the biocrude, and thereby reduce catalyst poisoning in the main hydrotreater due to metal deposition. We are evaluating two guard-bed configurations: a slurry bubble column and a trickle-bed hydrotreater to reduce the metal content <10 ppm before the main hydrotreater. The goal is to achieve a modeled hydrotreater catalyst life of 1 year

by doing long-term catalyst lifetime testing for over 2,000 hours. We plan to use the extended time-on-stream run to look at deactivation of the catalyst as a function of position, as well as learn about the deactivation rate based on the change in activity with time. Based on the slope of deactivation and the local deactivation rates (top vs. the main section of catalyst bed), we believe we can achieve a modeled catalyst life of >1 year.

- Understanding how the "blended feed tests…support the claimed order-of-magnitude increase in HTL plant size and associated decrease in fuel price." A key to larger HTL facilities is combining multiple wet-waste feedstocks beyond just sewage sludge. The resource assessment team showed that if they opened up the feedstock composition fed to an HTL facility to include food waste as well as FOG, the plant can afford the transportation costs necessary to justify a 1,000-ton-per-day plant. We showed experimentally that the alternative food wastes provide similar or better yields as compared to stand-alone sewage sludge processing. These data give us confidence that an HTL plant handling a variety of wet-waste feedstocks will have the same process performance and yields as that of a sewage sludge-only process.

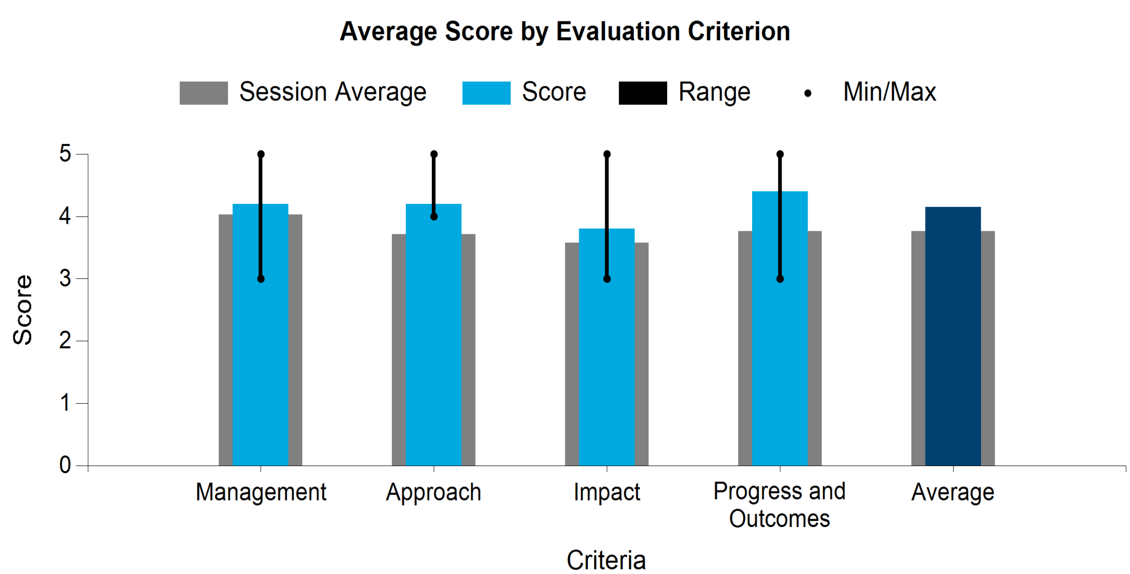
BIOGAS TO LIQUID FUELS AND CHEMICALS USING A METHANOTROPHIC MICROORGANISM

National Renewable Energy Laboratory

PROJECT DESCRIPTION

WBS:	2.3.2.102
Presenter(s):	Adam Bratis; Michael Guarnieri; Zia Abdullah; Courtney Payne; Jessica Krupa
Project Start Date:	10/01/2013
Planned Project End Date:	09/30/2021
Total DOE Funding:	$1,200,000

Biogas derived from anaerobic digestion of waste streams such as biorefinery wastewater and animal, agricultural, and municipal solid waste offers a versatile renewable energy source. Total domestic methane potential from landfill material, animal manure, wastewater, and organic waste, combined with biogas generated from AD of lignocellulosic biomass, is estimated to offer >4 quadrillion Btu potential energy. This energy could displace nearly half of current domestic natural gas consumption in the electric power sector and all consumption in the transportation sector. However, despite the promise of this feedstock, its gaseous state prevents facile integration with extant transportation and industrial infrastructure. Microbial conversion of biogas to liquid fuel and chemical intermediates offers valorization potential. However, biogas biocatalysis is currently limited by poor substrate gas-to-liquid mass transfer, low conversion efficiencies, and incomplete biogas utilization. To this end, the Biogas Biocatalysis annual operating plan aims to develop a carbon- and energy-efficient biogas bioconversion process via techno-economic-informed strain and fermentation engineering strategies. Efforts here will improve both process economics and sustainability via process-intensified, carbon-efficient biogas bioconversion to value-added platform molecules, enabling bolt-on deployment for valorization of biogas derived from stand-alone AD infrastructure.



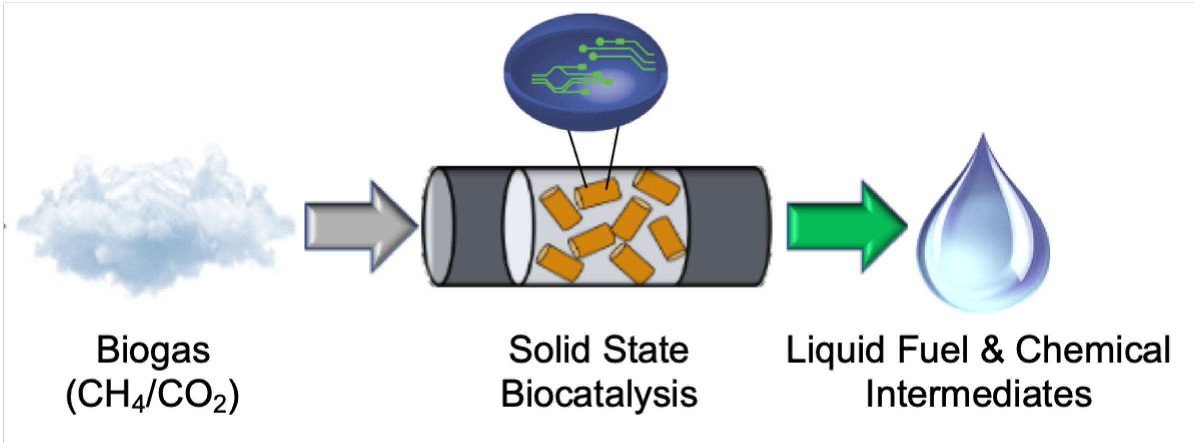


Photo courtesy of NREL

COMMENTS

- Delegated authority to manage minor research developments. Clearly articulated elevation and standards around change management. Large number of material transfer agreements. Have developed a large toolbox to tailor methanotrophs and optimize to this process. Also potentially licensable intellectual property to someone else working in this space. Pretty impressive results demonstrating marked increases in C1 rate and yields. Which year's SOT was this? Q2 milestone should also have a purity or ease-of-separation milestone. Lower yields with easy separations is the other side of the coin from high yields with difficult separations. Seem to have engaged a number of industry partners. Who, if anyone, is interested in commercializing this intellectual property? Are they interested in the whole or the enabling developments? Responsive to comments from previous review processes. No comment on risk identification and mitigation strategies. Probably more of a "how did we react," given that this project is closer to the end than the beginning. Need to tie/relate intermediate metrics back to the overall metrics of >$0.25/GGE. Team has truly made a lot of technological progress around an early-stage technology. Advances like these should help the project adjust quickly at larger scales. Need to help with the transition out of the laboratory setting. Solid-state processing (biological immobilization) is pretty nifty. Very knowledgeable presenter, and diverse team with strong technical underpinnings. Are doing a few things to answer research questions, which might not be economical at a commercial scale.

- Project has a good management plan. Data so far look very promising. Good risk identification and mitigation plan. Have some concerns about the stability of the microorganisms under varying conditions (caused by variation in waste stream). Would like to see more information on organism growth and decay rates and how they are managed in the biocatalyst, and regeneration or replacement rate of biocatalyst. Also would like to have more information on any waste streams from this process and disposal concerns.

- Strengths: Clear communication and collaboration with Lawrence Livermore National Laboratory. Demonstrates valuable industry potential with the addition of a biocatalyst unit at existing digestors for fuels and chemicals production. Significant advancements have been made toward converting CO_2 and CH_4 into 3-hydroxybutyrate via biomass production. Bioreactor internal development enables multiphase fermentation to occur (gas feedstock, solid substrate, liquid product). Valuable advancement in microbe strain for increased acid tolerance.

  Weaknesses: Additional industry partnerships for advice on challenges and limitations to commercializing a biocatalyst would add value to this project. The project would benefit from investigative work into the technology and cost required to extract and purify identified products (e.g., 3-hydroxybutyrate). It was difficult to determine whether there was lost performance due to the 3D-printed substrate exhibiting contamination or fouling. This will be valuable information for understanding the long-term commercial operability. The priority around the suite of other fuels and polymer intermediate was vague. It would be valuable to use commercial and market data for prioritizing microbe pathway development

- The project management is very strong. This is a very exciting project. There is a lot of potential impact beyond the goals of the project, with respect to the reactor design and technology and the genetic engineering tools that were developed. This is a fairly early stage, but there seem to be a lot of directions that the work can go in, particularly given the new reactor design. The approach is very focused. There are a few considerations that should be incorporated into future work or at a minimum into the LCA/TEA, particularly the disposal of the scaffold structure/hydrogel/biomass. Also, data with real biogas will be important to see how the system functions when fed contaminants, how the strain functions long-term, and how well the system resists biomass escape and contamination from the influent stream/piping.

- This project seeks to upgrade biogas to more valuable liquid products using genetic engineering and biocatalysis. This concept merging metabolic engineering of methanotrophic bacteria with catalysis to produce high-value liquid products instead of methane gas is very innovative The project management is appropriate with a good mix of disciplines. The general approach, goals, and challenges are clear, although risk mitigations are not discussed. The end target of greater than $0.25/GGE and greater than 5% carbon yield increase seems like a relatively low bar to justify a new approach/technology. The impact of conversion of biogas to a variety of high-value liquid products is highly significant and fully consistent with BETO's goals while improving the chance of economic viability. The achievements presented as this project reaches its end are very impressive, particularly the genetic engineering advancements demonstrated (though it would help if the genomic jargon/diagrams were avoided in favor of more accessible descriptions for a wider, though still technical, audience). The biocatalyst structure and microbe immobilization is novel, though it would have been interesting to see the rest of the reactor design that holds the solid scaffold, especially given the concerns about mass transfer. It is good to be aware of potential mass-transfer issues now, as this may be a challenge for successful scale-up. However, the biggest challenge to scale-up at the present time appears to be catalyst cost, the relatively short catalyst lifetime, and the inability of a mechanism for catalyst regeneration as in abiotic catalysts. Solutions will need to be developed for this project to realize its full potential.

PI RESPONSE TO REVIEWER COMMENTS

- We thank the reviewers for their encouraging and constructive feedback. As highlighted by the review team, this project offers an innovative and disruptive route to biogas conversion via an integrated approach, encompassing biocatalyst and bioreactor engineering, in silico analyses, and TEAs. We feel this work specifically addresses BETO efforts to diversify its feedstock portfolio, while concurrently improving the economics and carbon intensity of waste conversion and biorefining. Additionally, as noted by the review team, the impact of conversion of biogas to a variety of high-value liquid products is highly significant and fully consistent with BETO's goals, while improving the chances of economic viability. Our team is excited about the broad potential impact this work will have on BETO's conversion platform, as well as the larger biogas industry and bioeconomy as a whole.

  The reviewers raise an excellent point regarding yield vs. separations: "lower yields with easy separations is the other side of the coin from high yields with difficult separations." Notably, the proposed reactor design enables high-yield, in situ product separations via direct gas-to-liquid conversion. No further separations intensity (e.g., pH swing or distillation) is required to recover organic acids at bench scale; excreted products can be recovered via gravity flow, resulting in product with >90% purity and concentration suitable for direct catalytic upgrading. However, we expect separations at larger scale may require more intensive/active recovery efforts (e.g., intermittent reactor wash and/or product concentration). We are actively evaluating intermittent delivery of product recovery liquid in our newly designed prototype reactor and will evaluate and incorporate this as a key parameter in future TEA (discussed further below).

With regard to industry engagement, we agree with the reviewers' assertion that formalized inclusion of industry partners, in an advisory and/or developmental capacity, would be of great value to future project pursuits. Following discussions with our project manager, BETO has expressed support to expand the project scope to include such industry onboarding in the next period of performance. To this end, we have identified and engaged industry partners eager to support development and/or pilot-scale deployment efforts; we will seek to finalize and formalize partnership(s) prior to initiation of FY 2022 work.

The reviewers accurately noted a series of potential hurdles related to biocatalyst deployment at scale. With regard to biocatalyst stability, our prior period of performance established our top-candidate biocatalysts as highly robust and substrate-tolerant; we successfully cultivated hosts on raw (untreated) anaerobic digestion biogas streams containing siloxanes and H_2S concentrations exceeding 10,000 ppm, with no impact upon performance. Regarding biocatalyst lifetime, we have notably achieved continuous methane uptake with no decrease in rate for a minimum of 3 months. Additionally, we have not observed any biocatalyst fouling during these 3-month conversion trials at bench scale. However, we are in strong agreement with the reviewers that defining biocatalyst lifetime and incorporating biocatalyst regeneration (and/or disposal) requirements and metrics into TEA and LCA models will be essential to assess process viability at scale. Dedicated TEA will be a key component of our follow-on period of performance and will inform biocatalyst, materials, and reactor compatibility and optimization, as well as further defining waste disposal and additional product separations and upgrading requirements, if any. Notably, end period-of-performance metrics, including >$0.25/GGE cost reduction and >5% carbon yield increase in a conventional lignocellulosic refinery context, reflect the amount of input carbon diverted to waste processing via anaerobic digestion (~10%–20%). For example, a $0.25/GGE cost reduction reflects ~10% of the BETO target minimum fuel selling price (~$2.50/GGE), which is a substantial contribution from a bolt-on waste upgrading technology. We have successfully achieved productivity metrics to satisfy such TEA and LCA requirements. However, as noted in our presentation, there are over 2,000 operational AD units in the United States. Thus, we are also encouraged by the potential to deploy this technology in additional process configurations, such as direct interfacing with municipal wastewater treatment or agricultural AD units. The aforementioned TEA efforts will establish a baseline for such "stand-alone" biogas conversion configurations in the coming year.

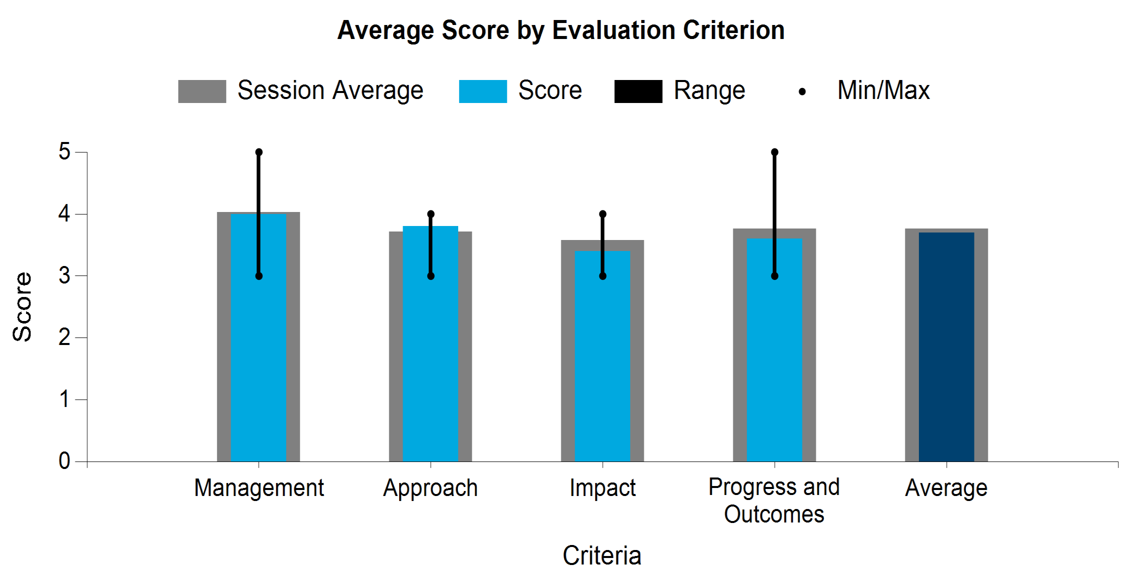
SEPARATIONS IN SUPPORT OF ARRESTING ANAEROBIC DIGESTION

National Renewable Energy Laboratory

PROJECT DESCRIPTION

WBS:	2.3.2.107
Presenter(s):	Adam Bratis; Eric Karp; Michelle Nolker; Zia Abdullah; Courtney Payne
Project Start Date:	10/01/2017
Planned Project End Date:	09/30/2020
Total DOE Funding:	$750,000

In support of BETO in converting organic waste feedstocks to fuels and chemicals, this project develops and demonstrates an advanced system for the production of platform carboxylic acids by arresting AD of wet-waste feedstocks. The project addresses three technology barriers in developing the bioeconomy: (1) feedstock availability and cost, (2) selective separation of organic acid species, and (3) first-of-a-kind technology development. This project has developed an advanced arrested AD system with separations that can operate in high-solids environments (>10 wt %) and is net positive in energy consumption compared to the energy content of the carboxylic acids. Operating an in situ product recovery system in high solids is required for fermentation-produced intermediates beyond ethanol that have volatilities less than water (e.g., carboxylic acids). Carboxylic acids form a versatile platform for the production of renewable diesel fuel, aviation fuel, monomers, and chemicals. A high-solids in situ product recovery system expands the feedstocks for arrested AD, which have been restricted to thin stillage, to solid food waste. Additionally, current arrested AD technology employs separations that consume >200x the energy content of the produced acids. This project has developed and demonstrated the first arrested AD technology with in situ product recovery that is net negative in energy value and operates in solids contents >10 wt % to produce a mixed carboxylic acid product that is carbon-negative.



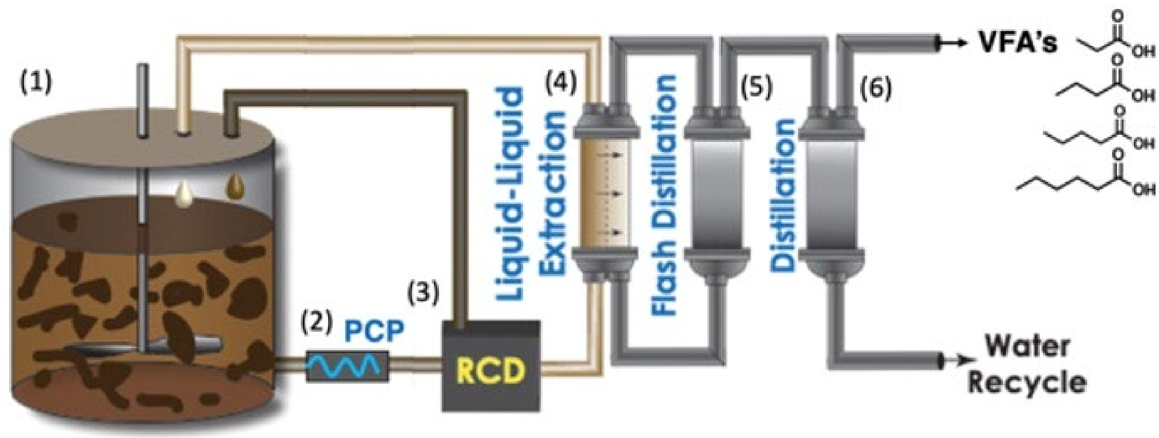


Photo courtesy of NREL

COMMENTS

- Collaboration across many projects. Seem to prefer collaboration and communication predicated on proximity. Not bad, but may miss broader opportunities. On slide 11, the two y-axes sell the advances of the rotary ceramic disk short. What about the long-term stability of the membrane after many cleaning/wash cycles? Not quite clear on the comparison to base. They are generating substantially more and longer carboxylic acids. Certainly the higher purity is a good thing, but it is not an apples-to-apples comparison. Clearly focused on an AD system with dramatically decreased energy consumption. The rotary ceramic disk seems like a really big advance; not as certain about the other elements of this project. Unclear if any of the external collaborations generated any tangible impact upon this project. There were a lot of them, and many are with well-respected organizations. Project seems to have been managed well without any issue. Seems like the processes and people could work together well again if needed. Net-energy-positive separation is a major step forward, as it takes a common and large cost center and makes it into a savings opportunity. High solids loading rate is impressive. Seems like this project made advances in areas, but struggled as the parts came together. Think it will be critical to share the individual process advancements and collaborate to really magnify the impacts of some of the achievements. Should be able to present a clear matching up of original goals for the project and achievements. Left with the question of what is next for this work. Probably need to do some microbial analysis and optimization.

- Strengths: Strong cross-collaboration with other lab research efforts (e.g., Los Alamos National Laboratory, PNNL). Clear value creation opportunity through carboxylic acids for intermediate fuel and chemical production. Opportunity for value creation on existing anaerobic digestors through transfer from low-value biogas to higher-valued carboxylic acids. Clear advancement of ceramic disk membranes in their application in carboxylic acid removal.

  Weaknesses: More clarity around the commercial operation of ash purging is required (e.g., how this will occur on a continuous basis). Difficult to understand the relationship between slower pump speed within the digestion to handle the solids content and the bioreactor flow rate CapEx requirements. More investigation into the flux decline and membrane recovery is needed. Important to understand this relationship with capital investment and operation performance at commercial scale. More experimental work required to determine bioreactor parameters for optimal chain elongation.

- The project appears to be small and very clearly managed. It appears that the project has been completed, but it was not clear whether this overall area of research will be continued. The research appears to be early-stage. Technical difficulties regarding the high solids pumping and filtration with the rotating ceramic disk were very well managed. Results are promising, but it is not clear how stable the system is or how well the microbial activity will scale. It seems worth continuing to pursue this research to determine whether the system can be operated for longer time periods with good performance, and also how well it scales.

- This project has shown successful progress and very interesting results. As I look toward the potential of commercialization, I have some concerns, especially around process control at pH 5 and the uniformity of feedstock. Would like to see a discussion on pretreatment of feedstock and if particle size impacts rates or end products. Also would like to see a mass balance and a discussion on the fate of solids remaining after this process. All of these impact commercialization and acceptance. Would also like to see a discussion on the impact of any recycle streams to a WRRF and how they might impact nutrient removal or permit compliance.

- This project is focused on developing the downstream components to an arrested AD system to separate and purify the target volatile fatty acid (VFA) product. Work on the upstream biological portion is performed by a different NREL team and was not reviewed in this Organic Waste session. Collaboration between the NREL groups is evident and a good part of the project management. The approach of engineering a separations system configuration that that can handle high solids loading and is energy-efficient is straightforward but not obvious or easy. The presentation did an excellent job of explaining each step of the separations process developed. In particular, the use of the rotating ceramic disk as a filtration device appears to offer adequate VFA separation without plugging at low energy cost (by two orders of magnitude) and is scalable, which makes this a significant development and possible game changer. The fact that the project also demonstrated operation at high solids content and that the process is notably less complex than the current state of the art for separations is also a good achievement. The fact that the chain length of VFA products is smaller than that desired and achieved by the current state of the art is disappointing and calls into question the value of the complete process, though to be fair, chain length is a problem that needs to be addressed by the upstream arrested AD biology and is not the fault of the separations work being reviewed in this project. The performance of integrated runs is also an important result, although the scale is still smaller than is needed to assess potential commercial viability. Further, the true cost of the proposed process cannot be assessed until it is determined what additional upgrading is necessary for the separated VFAs to become final sellable products. Nevertheless, the proposed separations process represents an overall innovative and promising approach to purifying VFAs from a high-solids feed at a relatively low energy cost.

PI RESPONSE TO REVIEWER COMMENTS

- We appreciate the valuable feedback from the reviewers. This project developed a first-of-a-kind separations system that is cable of in situ extraction of acids in a high-solids environment. The scope of the last 3 years was to build, validate, and demonstrate the system on a real-world biological system with food waste as the feedstock. Future scope of the project would include a greater focus on the overall system mass balances, recycle streams, water footprint, and optimization of the biological process. Another key area for future work is understanding how the in situ extraction of acids affects the biological process and optimizing both of these processes to increase yield of the VFA product.

  The project has ended. However, we aim to continue this research with interested industrial partners in scale-up of the system through applicable funding opportunity announcements. Through such a project, a broader TEA, LCA, and time-on-stream study can be addressed. With process optimization and tackling multiple key process variables, including feeding and recirculation rates, in addition to the enrichment of VFA-producing bacteria rather than lactic acid bacteria (which are less tolerant to low pH), the system can be stable at pH values around 4.5 when operated in continuous mode. We also note there are multiple examples of two-stage anerobic digestion systems where the first unit (with major production of VFA) self-regulates at pH 4.5–5 without the need of external pH control.

The disk membrane was operated for 7 days continuously without the need for a cleaning cycle. The permeate rate was 4 mL/min, which processed the entire digester volume every 25 hours. Future work is needed for longer time-on-stream studies and investigation of cleaning cycles. In this integrated run, the flux was restored entirely with a 10-minute back flush with water. For longer time on stream, we anticipate the need for a chemical cleaning (~10 wt % NaOH) at some point. To address this, the system needs to be run for longer times and larger scales. We hope to address this in a future project. Lastly, note that the rotating ceramic disk was not compared head-to-head to traditional tangential flow filtration because tangential flow filtration has zero permeance above 7 wt % solids and could not be used in this application.

External collaborators on the project were informal collaborations for waste feedstock supply, and activated sludge was used as initial microbial inoculum. By having access to regional waste streams, we were able to work with freshly collected material and avoid degradation due to shipping.

INTEGRATED BIOREFINERY FOR CHEMICAL AND FUEL PRODUCTION FROM WASTE BIOMASS

Visolis

PROJECT DESCRIPTION

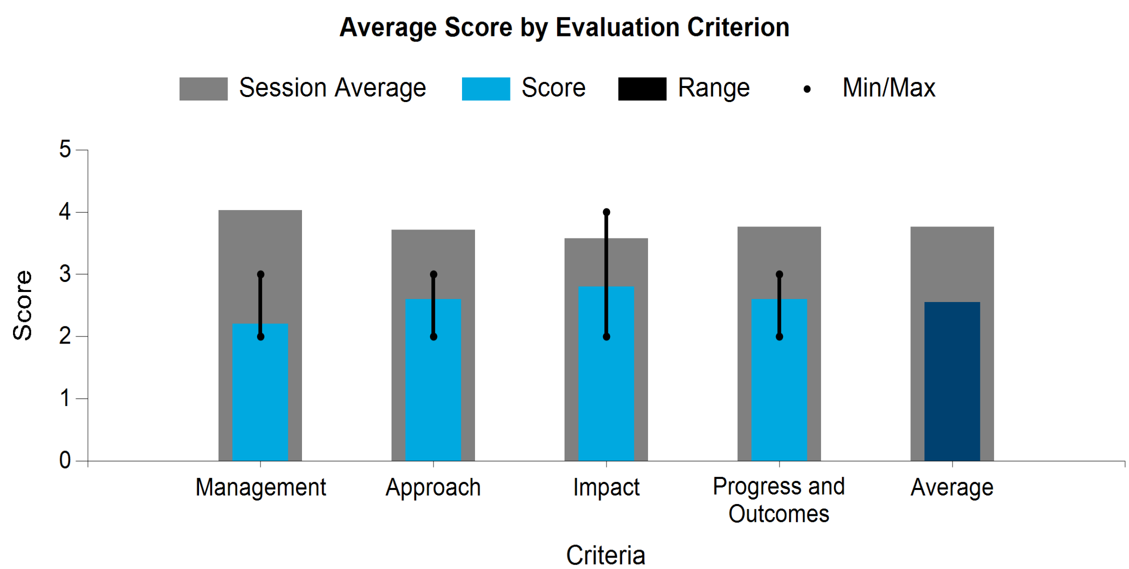
WBS:	2.3.2.221
Presenter(s):	Deepak Dugar
Project Start Date:	10/01/2018
Planned Project End Date:	09/30/2022
Total DOE Funding:	$1,999,333

One promising technology to reduce and reuse organic waste, including food waste, agricultural residues, and municipal solid waste, is anaerobic digestion, whereby a community of microbes breaks down complex organic molecules into biogas. Biogas, however, is of limited value, which prevents anaerobic digestion from being widely deployed.

Visolis aims to develop a novel hybrid process to rewire anaerobic digestion with arrested methanogenesis (ADAM) to produce a liquid intermediate instead of volatile biogas. The intermediate will then be used as a feedstock to upgrade to a range of high-value bioproducts and renewable fuels.

The key technology that will be developed under the grant is a process to selectively concentrate the liquid intermediate from the ADAM effluent. This concentrated intermediate will then be used as feedstock for Visolis' proprietary engineered microbes that will convert it into a platform molecule (PM1) at high titers. We will then catalytically upgrade PM1 into a variety of valuable chemicals, including polymers and second-generation biofuels.

We have been able to produce high titers of the liquid intermediate in the ADAM process and developed a process for filtering and clarifying the ADAM effluent, as well as optimizing the process for selective concentration of the intermediate from the ADAM effluent. We are close to hitting target titers for PM1 production from the liquid intermediate. The major challenge in the second half of this project will be integrating all the different unit operations at the project site.



COMMENTS

- Scores reflect a poor level of candor about the spending of public funds from the U.S. Department of Energy. Wish the identity of PM1 was not hidden. Curious as to how the cumulative titer target is already exceeded. Graphs should have values on the axes. There is discussion of risks and the accompanying mitigation strategies. There is limited discussion about the team's communication and collaboration. Visolis also appears to be playing this project very close to the chest, which will make communication much more difficult. Is Visolis situated on the University of California, Davis campus? Connection with Argonne? Resin-wafer electrodeionization optimization? The level of rigor presented on how these targets make a measurable impact on BETO's targets and goals is lacking. What is the intended model to finance/operate commercial units? Team seems to be making progress, but it's not clear against what baseline. There is a lot of switching between model and real streams in these slides. The goal of getting to a platform molecule is ideal, but it's also important to get to a sufficient scale to enable logistics. Are these targets sufficient to get to the ultimate project goal? Limited information on this front. Do the projected costs take into account the logistics of the hub-and-spoke model? Level of rigor of this research as presented just not as high as the other work in this portfolio. Could either be choosing to withhold information, or could be lesser research. Presenter did seem knowledgeable, so it is probably the former.

- Strengths: Partnership with University of California, Davis is valuable as it enables scaled digestion sludge from a two-step anaerobic digestion system being applied to the research work. If successful, a pathway from digestion to fuels/chemicals at regional wastewater treatment plants would bring significant impacts to these regions. Progression was demonstrated toward increasing PM1 titer through fermentation operation improvements and pre-clarification of ADAM feedstock.

  Weaknesses: There was minimal discussion about the partners within the project, how these partners participate, and how communication between them is managed for effective project execution. It was impossible to assess the approach and its merits because no detailed information was provided for the secondary aerobic digestion process to product PM1 or the separation needs for the creation of value-add fuels/products. Could not determine what the upgrading aerobic digestion process was actually doing. No information provided on the process parameters, the waste streams, the quality of the products, and whether they were of commercial value. There was no information as to what PM1 was. Did not know what suite of chemicals were being produced, how they would be separated, and what contaminants of concern were in this product stream. The CapEx impact was difficult to rectify. There was information that showed $25 million for a commercial plant, while another slide showed $2–$5 million. There were not units on any of the graphs, making it impossible to determine what progress had been made and whether the accomplishments were significant.

- The presentation and state of the project are very hard to evaluate given the lack of details and lack of numbers provided. Figures lacked axis numbers and legends. Targets lack numbers. It was unclear what the targets were and why. It was unclear how this project/targets compared to other projects and current practice. The described approach is vague ("multiple samples," "multiple approaches," "multiple paths to success," "industrial partners"). Overall, the project was very difficult to assess. It was unclear which waste streams are being targeted for the technology (type, quantities, options, etc.). Currently food waste is being used, but it is unclear what the plans are for testing other feedstocks or blended feedstocks. It is unclear how close to optimal the microbial feed produced via ADAM is. It is unclear how much more work is needed at this step. It seems that the clarification and concentration steps will be performed at the same site as the ADAM process; nevertheless, it was unclear where the waste streams from these processes will go, whether there were concerns regarding treatment of these streams, and what their chemical makeup was. More information on the planned scale-up of clarification and the feasibility of clarification and concentration at scale will be useful.

- The project has achieved some very interesting results, but I am unsure how this will be implemented at small communities. I would like to see a process flow diagram of what would be included in the small community process. Although a projected CapEx was discussed, there was no mention of the operating expenditures, which could be significant for a small community. In addition to CapEx and operating expenditures, there is the cost for transport of the microbial feed. Also concerned about disposal options for the remaining solids. Would like to see a mass balance and more details to support the cost savings for small communities.

- The proposed process in this project uses ADAM of food waste to produce volatile fatty acids, which are then extracted, concentrated, converted via biological action to an unidentified key intermediate species, and then transformed via catalytic reactions to various high-value chemicals. From a top level, the general steps in the process and its objective of deriving high-value chemicals from ADAM of waste instead of low-value biogas are clear, and its impact, if successful, will be significant. However, insufficient information is provided to understand what specifically is being done in this project in order to assess its progress and viability. The project management is not adequately described—specific tasks and milestones are not identified, functions for the stated team members are not stated, and industrial partners and their roles and methods of communication are not identified. Little to no information is provided on the extraction, concentration, biological conversion to the unidentified platform molecule 1 (PM1), and subsequent catalytic conversion steps. There is no clear identification of the cost or energy requirements of this fairly complex process to understand the context and significance of the little hard data that is provided. None of the claims mentioned in the summary, which are significant, are described or justified in the presentation, making it impossible to verify. The level of detail provided in this presentation is comparable to that of a marketing brochure, which is not sufficient for a technical project status update when trying to assess progress. It is understood that projects have proprietary aspects that need to be protected, but this must be balanced against the need to provide sufficient technical detail to understand the level and significance of accomplishment, especially when public funding is involved.

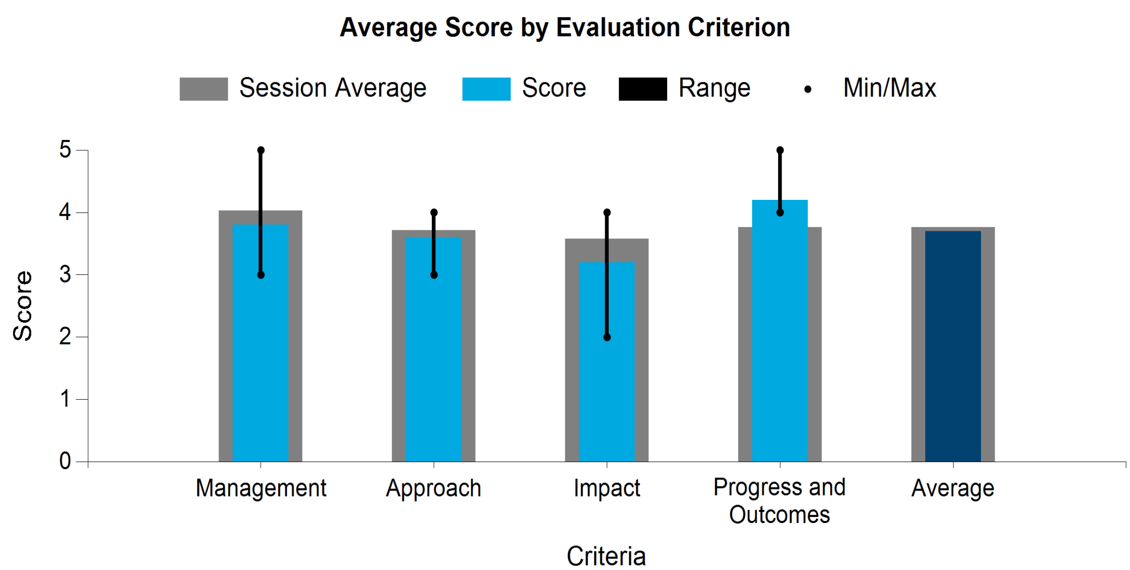
NOVEL AND VIABLE TECHNOLOGIES FOR CONVERTING WET ORGANIC WASTE STREAMS TO HIGHER-VALUE PRODUCTS

Research Foundation for the State University of New York, University of Albany

PROJECT DESCRIPTION

WBS:	2.3.2.226
Presenter(s):	Yanna Liang
Project Start Date:	10/01/2019
Planned Project End Date:	02/28/2023
Total DOE Funding:	$2,698,542

The overarching goal of this project is to develop an integrated and efficient process for converting wet organic wastes to VFAs. To achieve this goal, we aim to accomplish seven different objectives: (1) identification of the optimal pretreatment method for each target waste stream; (2) determination of the best process parameters for arrested methanogenesis (AM); (3) evaluation of product yield and titer of VFAs from the waste streams separately through microbial electrosynthesis (MES) with CO_2 capture and conversion; (4) developing an innovative membrane-based liquid-liquid extraction process for extracting VFAs and other organic acids out of the fermentation broth; (5) performing preliminary LCA and TEA for each process block and the overall process; (6) operating the integrated process continuously at a 5-liter scale for at least 3 months; and (7) operating the integrated process continuously at a 50-liter scale for at least 100 hours. TEA and LCA will be performed for this operation. Upon finishing all proposed objectives, we expect to have developed one of the first scalable, economically competitive, and environmentally sound processes for converting wet organic waste streams to high-value products.



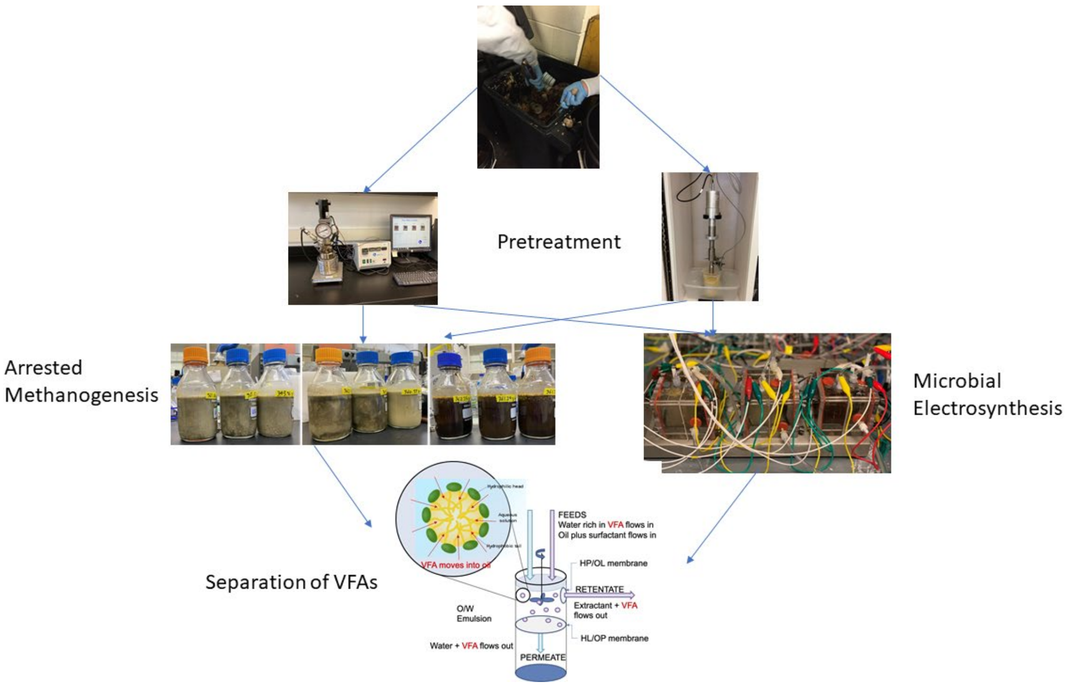


Photo courtesy of the Research Foundation for The State University of New York, University of Albany

COMMENTS

- Strengths: Good research partnerships within the project. Credible method of communication and collaboration. Novel application of food waste pretreatment (HTL, ultrasonication) before undertaking VFA production. Clear progress toward improved VFA production through ultrasonication pretreatment. Positive demonstration of microbial electrosynthesis pathway for CO_2 to acetic acid.

  Weaknesses: The project could value from more active advisory from commercial or industry partners (e.g., support in validating economics, understand the market for VFAs and the purity required). Difficult to determine whether the significant increase in capital expenditure for this series of unit operations is recoverable through the increase in product value (i.e., does the TEA still suggest profitability to the commercial operator despite the significant increase in CapEx from the new unit operations?). Will need to determine the significance of the ultrasonication and electrosynthesis on the operation cost (primarily the electricity) to determine viability at scale.

- The focus of this project is on various improvements to the pretreatment, production, and separation of VFA products from wet wastes via an AM process. Project management appears to be adequate. The overall task description and approach is clear and includes a description of the current state of the art for each task, which helps gauge the level of innovation. However, it is not entirely clear what VFA species are targeted for production, what the market is for each species, and whether these are the end products or just chemical intermediates that must be further processed once separated. The benefits of ultrasonication for food waste pretreatment are encouraging, though it is not clear what the specific innovation in AM itself is for meeting the stated target of >20-g/L VFAs. The use of MES for conversion of carbon dioxide produced during AM directly to VFAs instead of just methane is an important aspect and could be a significant advancement if successful. However, there is insufficient description of the MES process, including catalyst identity, specific microbes, and the energy cost to fully assess its value. The extraction step (CLEANS) similarly appears to be a unique and promising approach for VFA separation, but it is not clear how the extracted VFAs are further separated from the extractant to get to the final product and what happens to the remaining aqueous phase. The incorporation of tasks dedicated for demonstrating operation of the integrated process at two scale-up capacities (5 and 50 liters) are important aspects of this project, but no specific details as to how and where this will be done were provided. If successful, the improved carbon conversion to value-enhanced chemicals (i.e., VFAs as opposed to biogas) in AM is consistent with BETO's goals and could have significant impact.

- The interrelationship between all of the goals, targets, and tasks was a bit difficult to suss out from reading the slides. Presenter did a good job of relating the different facets of the project to each other. Like the start and the overview of the project. Internal project communication is sufficient. Unclear on the degree of external communication both to other projects in the BETO program and beyond. The interfacing of the tasks focused on AM, VFA, MES, etc. isn't quite clear. Are the outcomes of one task or the other influencing work in another? Just a lot of work that appears to be conducted in parallel to other work. Are the goals ambitious enough? VFA titer is met in untreated feedstock in double the time. Would be clearer to tie this number back to operational values to show that half the time equals a significant improvement. Goal here is to push toward showing that the project really is tackling the critical barriers to commercialization. Project has met all milestones to date, and seems to have navigated through the early stages without any issue. There does not appear to be any focus on commercialization or industry engagement in this project. It is tackling a tough issue if the goal is to adjust the output of AD units toward VFAs and other higher-value products. Might be able to borrow some of the TEA framework from other projects funded by DOE, instead of creating the element de novo. How resilient are the pretreatment results to the high variability of food waste?

- The management plan is clear and well laid out. The approach is also clear. The project is ambitious, but is clearly laid out. The extraction method using emulsions is clever. Integration of the unit operations will be a challenge. The PI seems to have a dual focus on comparing AM and MES but also considering their incorporation in series. I think this is a good approach. The results are clear and promising. The various side streams and waste products should be considered and incorporated into the TEA/LCA.

- There are positive results on this project; however, there are some weaknesses. There should be a more detailed discussion on the communication plan. The AM process will produce solids. I am concerned about the fate of digestate from the AM process. I would like to see a mass balance around the process. I suspect the digestate will have some organic content, and in addition may have PFAS, which may impact the LCA and disposal options. Need to identify any recycle streams to the WRRF and what the potential impact might be.

PI RESPONSE TO REVIEWER COMMENTS

- We very much appreciate the reviewers' time and effort in providing critical evaluation and valuable feedback for this project. As discussed during the presentation, the whole team has been meeting monthly with the project manager over Zoom since the start of this project. In addition, meetings among team members have occurred frequently to enhance communication and ensure integration of different tasks. We are aware that not all organic content in the feedstocks will be converted to VFAs, and we are in the process of conducting a mass balance of organic carbon considering pretreatment and AM. We understand that sludge contains PFAS and these PFAS will be present in the residual digestate. Although PFAS are beyond what was proposed in the original proposal and are not included in the statement of project objectives, we have been actively testing different approaches to remove and destroy PFAS in the digestate after AM. PFAS in sludge and digestate, however, are not regulated by the U.S. Environmental Protection Agency at the time of writing. We will pay close attention to rules and regulations regarding PFAS and will update LCA and find suitable disposal options accordingly. Side streams and waste products from this project are residual digestate after AM and MES and raffinate from the separation unit. We will consider how to dispose each in a cost-effective and environmentally friendly way and will incorporate all of these into the TEA and LCA.

  Communication with BETO's technology manager and project manager has been ongoing frequently through emails and monthly meetings. For budget period 2, the AM and MES tasks are parallel to each other since each aims to maximize VFA titer and productivity from the same feedstocks, either untreated or treated. Entering budget period 3, we will integrate these two into one unit where the AM process could be conducted in the anode chamber of the MES. Or we may use digestate from AM as anolyte for MES. By doing so, we would achieve the highest VFA production rate from the target feedstocks and highest CO_2 conversion to VFAs.

We are aware that the TEA of AM has been funded and performed by DOE labs. We will surely borrow the established framework to speed up the TEA of this project. We agree that given the high variability of food waste, the pretreatment effect may be different. We are currently testing the effect of pretreatment on food waste sourced from different locations with different compositions. We strongly agree that an external advisory group will be beneficial for this project. We will assemble this group soon and get advice, suggestions, and recommendations from the members periodically.

We are also aware of the cost associated with each unit operation. The TEA will reveal what will be the key cost drivers. Based upon outputs from the TEA, we may adjust the unit operations to ensure the economic viability of this project. As shown in the slides, we have been targeting short-chain fatty acids (C1–C5) from food waste and sludge. These VFAs are natural products from the target wastes. Once extracted from the fermentation broth, they can be used for producing sustainable aviation fuels and as intermediates for producing other chemicals and products. The market for each VFA will be analyzed in the TEA framework.

We are deeply aware that BETO has funded several projects on AM. Results from AM as a part of this project will be compared to MES in terms of economic viability and life cycle impact. We agree that not much detail was provided for MES due to time constraint. We did mention during the presentation that the team has developed an effective nickel foam cathode for CO_2 conversion via hybrid inward electron mechanisms and an enriched microbial consortium that produced acetic acid at high titer from CO_2. All details are provided in our quarterly reports to DOE.

Regarding VFAs in extractant, we will use a stripping solution to recover the extractant for reuse. The aqueous phase could be sent to the fermenter, but eventually, it will need to be disposed properly. The scale-up studies at 5 and 50 liters will be performed in budget period 3. At both scales, all unit operations will be integrated seamlessly and tested. These scale-ups will be conducted at the University at Albany or Argonne National Laboratory pending further discussions.

ADVANCED PRETREATMENT/ANAEROBIC DIGESTION

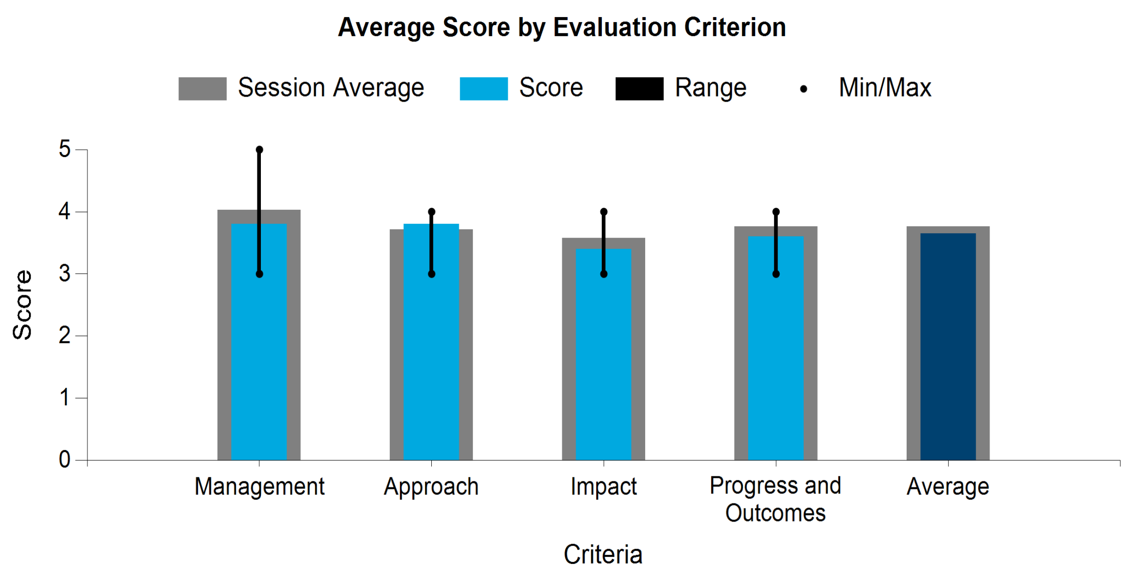
Washington State University

PROJECT DESCRIPTION

WBS:	2.3.2.228
Presenter(s):	Birgitte Ahring
Project Start Date:	10/01/2019
Planned Project End Date:	01/31/2023
Total DOE Funding:	$1,983,341

A total of 13,226 wastewater treatment plants in the United States (88% of all plants) are small (less than 5 dry tons of sludge per day). Conventional AD is in use at 1,233 of these wastewater plants, converting sludge from 53% of the total wastewater treated in the United States. Overall, only 40%–45% of the carbon in sewage sludge will be converted into biogas (approximately 60% methane/40% carbon dioxide), leaving 7.3 million ton/year of dry solids behind from conventional AD plants, which will need further disposal (land application, incineration, or landfilling). Our goal for this project is to improve the carbon conversion efficiency of sewage sludge during AD by at least 65%, resulting in a total conversion of ~70% of sewage sludge. This should be compared to an average conversion of ~43% during conventional AD. The advanced pretreatment/AD process includes a pretreatment step (advanced wet oxidation/steam explosion [AWOEx]) between two AD steps, along with upgrading of the biogas/removal of CO_2 with hydrogen into more methane. Producing renewable natural gas (RNG) will result in a higher-value energy product that can be supplied directly to the natural gas grid or used locally as a transportation fuel. This means that the advanced pretreatment/AD process is producing far more useful energy product due to both pretreatment and CO_2 conversion, and will further have a lower carbon footprint through the sequestration of CO_2 into more methane.

Our main hypothesis is that a viable solution for validating sewage sludge even at small wastewater treatment facilities can be developed by adding AWOEx pretreatment to selectively handle the recalcitrant part of the raw material and by upgrading the biogas into methane, which can be added to the gas grid or used locally as a transportation fuel.



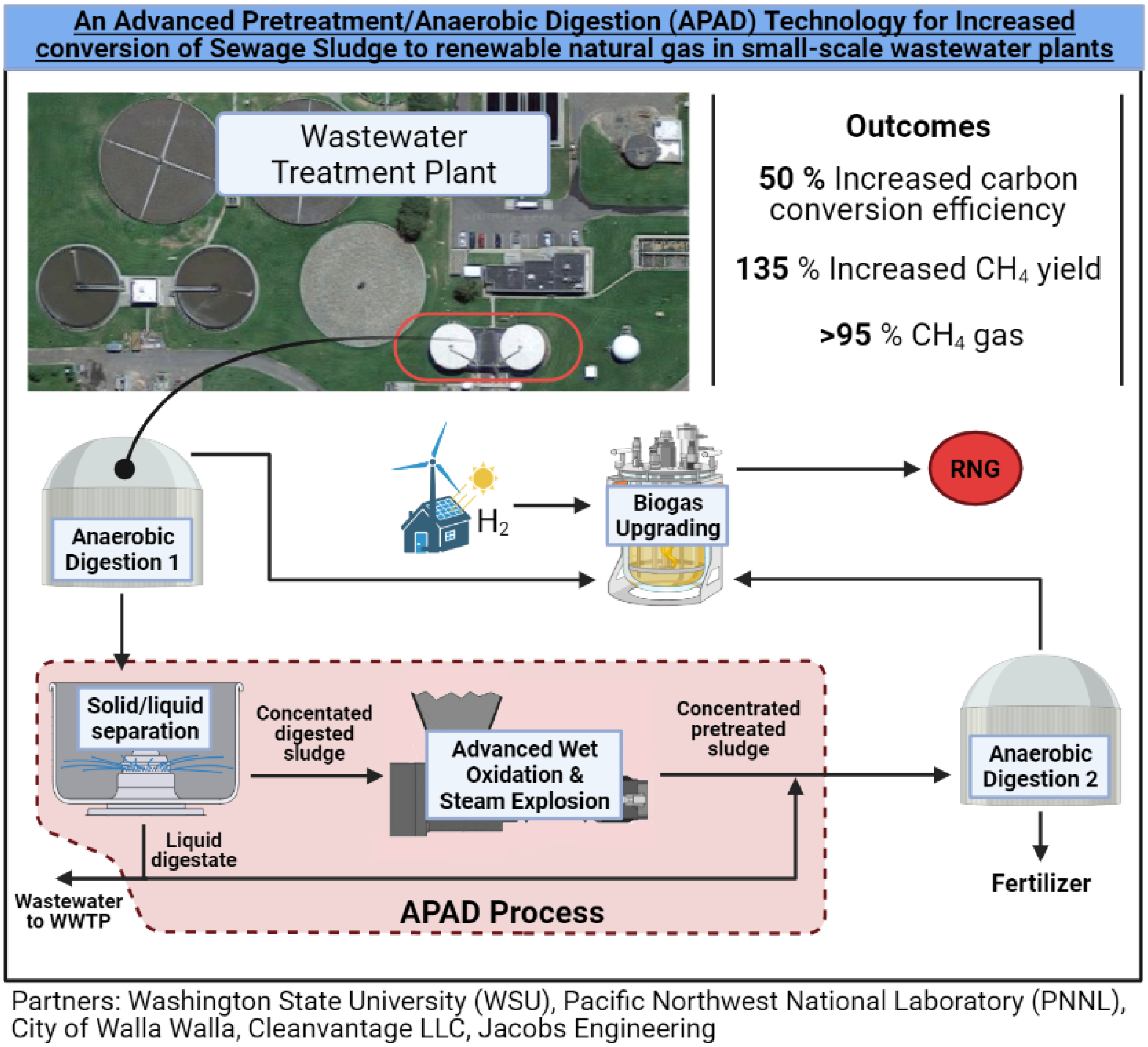


Photo courtesy of Washington State University

COMMENTS

- Limited discussion on management and risk identification and mitigation strategies. Would like to see a mass and COD balance. Need to understand the disposal options for the biosolids and if PFAS will impact disposal options. Need to understand if there is any recycle stream to the WRRF and the potential impact.

- Really early to judge this work. Seems to be on track at this early stage. While carbon conversion efficiency is critical, it is only a proxy (and useful) if it produces value for the utility. Would like to see more along those lines of thinking. Also recommend looking at making sure the process is operationally simple and robust. There were a couple of spelling and reference errors. Unfortunately without much work to judge, this is weighted more than it would be normally. None has an appreciable impact on comprehension. Great to see involvement of two utilities and a manufacturer of flocculants using real waste streams. Have done work characterizing and segmenting their market. Have identified risks and mitigation strategies. Have clear roles for team members. Commercialization appears weak at this stage; certainly room to improve and refine as the research progresses. Criticality of the 25 wt % solids? Central to economics calculations. Would it be beneficial to go beyond that percent solids?

- Strengths: Good cross-discipline partnerships, including strong relationship with Walla Walla treatment plant. Strong progress on wet oxidation for increased methane yield. Clear impact potential through value creation for existing wastewater treatment plants in adding AWOEx technology.

  Weaknesses: Minimal information provided on methods of communication and schedule of engagement. Confirmation of performance for methane yields will be required with aeration rather than H_2O_2 as project progresses. Relationship between increased capital cost and operating cost from AWOEx and the increased revenue from pipeline-quality natural gas was not clear.

- The focus of this project is on improving the methane yield from the conventional AD process for sewage sludge by adding an oxidative treatment step for breakdown of recalcitrant components and converting carbon dioxide coproduct to methane. The project management is adequate, with a good choice of industrial partners; inclusion of a local wastewater treatment plant and company with plant operating experience in particular should help guide the project and improve chances of implementation of the proposed advanced pretreatment/AD technology. The overall approach and key innovations are clear, along with the description, conditions, and advantages of the AWOEx pretreatment technology. The associated milestones are also clear. However, the carbon dioxide conversion portion, which is an equally important part of the innovation, is not discussed at all. The pilot test task, which is presumed to involve integration and demonstration of the complete process, is also not described. The methane yield data and other results shown are encouraging given the recent effective start of the project. The oxidant in the AWOEx tests has a distinct impact on methane yield, though 9% hydrogen peroxide is a relatively high concentration, and it is not obvious how the use of pure oxygen (as intended going forward) will affect the results, especially if insufficient time was given for complete breakdown of peroxide before encountering the organic feed. Overall, while the objectives of this project are worthwhile and the intended bolt-on nature of the process should make it easier to apply to existing wastewater treatment plants, the advanced pretreatment/AD process appears to add a significant number of high-energy unit operations, high cost and quantity of consumables (pure oxygen and hydrogen), and complexity to the plant. It is not obvious that the associated increased capital and operating costs associated with advanced pretreatment/AD will justify the increase in relatively low-value biogas. This will need to be investigated early on by the TEA task to assess feasibility and cost drivers. The fact that the process goes from reducing conditions in the first digester to highly oxidative conditions in the AWOEx step back to reducing conditions in the second digester sounds like it could be problematic to control over long-term operations, especially in a biological system, and needs to be proven by testing the integrated process.

- The management plan is clear and well thought out. The approach is very logical and stepwise. The impact seems like it has the potential to be great and to reach an often-overlooked community (small wastewater treatment plants). The project has the right partners in place to have a large impact. Slow start but solid results now. Clear results and progress being made.

PI RESPONSE TO REVIEWER COMMENTS

- We would like to thank the reviewers for their constructive input. The project is only few months into execution, but it seems like all reviewers have grasped the overall ideas behind the project and see the potential of the project.

  For the questions and weaknesses mentioned, I have these comments:

- Reviewer 1: The 25% wt % solids goal was picked from previous experience with upscaling of the pretreatment technology. It will allow for pumping of the material after pretreatment with standard equipment, which can be difficult with higher dry matter material.

- Reviewer 2: As described in the presentation, the project will use oxygen, and not H_2O_2 as used for the preliminary data presented. Results obtained after the DOE review meeting have shown that oxygen provides the same extra biogas trend as seen with H_2O_2. The techno-economic work going on in the project will provide the relationship between the extra cost and increased revenue. Of importance will be the cost of input H_2 and final use of the RNG.

- Reviewer 3: The comment on management, risk, and mitigation is contrary to other reviewer comments (see my presentation on slides 6, 7, and 8). The mass balance for the documented base case is presented on slide 12, as well as the target mass balance for intermediate and final cases in progress. Thank you for the comment about PFAS and its impact on disposal options. We will discuss this with the Walla Walla wastewater treatment plant. The water stream after solid/liquid separation will return to the wastewater treatment plant (see slide 9). This is the same practice as done today for dewatering digested sewage sludge.
- Reviewer 4: Thank you for the positive words. It is encouraging!
- Reviewer 5: The presentation concentrated on overall project ideas and organization and initial results obtained during the short project period (WP 2 and WP 3). We have just started WP 5 on CO_2 conversion to methane with the construction of a new bioreactor (Gantt chart slide 14). Pilot testing (WP 6) will not start before next year after intermediate review. As mentioned to Reviewer 2, we have recently found the same encouraging trend using oxygen instead of H_2O_2. We fully agree with the reviewer that TEA is an important instrument to guide us during the project period to assess feasibility and cost drivers. To ensure optimal coordination within WP 7 (TEA/LCA), we have recently set up extra biweekly meetings between PNNL, Clean-Vantage, and Washington State University. This is in addition to our monthly project meeting. Oxygen added during the AWOEx pretreatment is reacting instantaneously with the biomass in the reactor after injection. No oxygen can be measured in the off-gas from the reactor or dissolved in the pretreated material. As presented (slide 10), the AWOEx process has been in long-term operations at a large-scale biogas facility in Denmark, resulting in 30% more biogas with no inhibition of the AD process.

ELECTRO-ENHANCED CONVERSION OF WET WASTE TO PRODUCTS BEYOND METHANE

Colorado State University

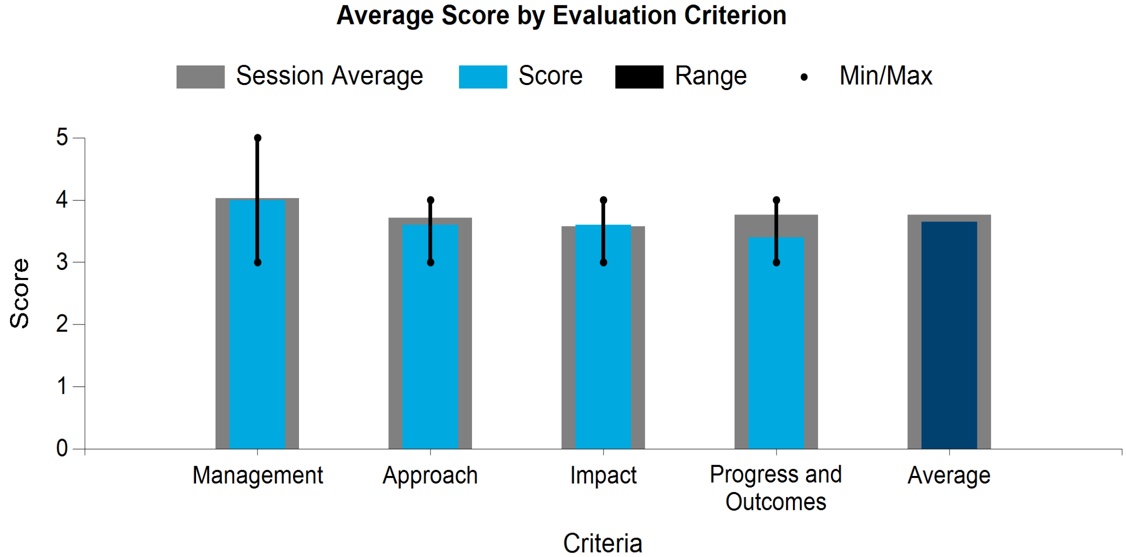
PROJECT DESCRIPTION

WBS:	2.3.4.605
Presenter(s):	Ken Reardon
Project Start Date:	10/01/2019
Planned Project End Date:	10/31/2025
Total DOE Funding:	$5,067,539

Wet organic waste presents problems in disposal cost and environmental impact and represents lost opportunities as inexpensive feedstocks to displace fossil-based products. AD, composting, and incineration strategies are limited by their CO_2 production (wasted C) and low-value/uncaptured methane production. Surplus renewable electricity could provide inexpensive electrons to enhance wet-waste processing and generate drop-in liquid transportation fuels.

The goal of this project is to address the current limitations of wet-waste conversion by incorporating microbial electrosynthesis of VFAs from CO_2, and elongating VFA chains to produce higher-value medium-chain fatty acids (hexanoic acid and others) and medium-chain alcohols (iso-butanol and others). The enhanced AD process will achieve higher VFA yields through consortia optimization, process parameter engineering (microaeration, pH, and temperature), in situ VFA removal, and AD electro-enhancement. Waste CO_2 from the digester will be upgraded using microbial fixation augmented by direct electron utilization to produce additional VFAs. In one approach to produce a higher-value product, the VFAs from both sources will be subjected to electro-enhanced microbial chain elongation, producing medium-chain fatty acids. A second approach will produce iso-butanol through microbial electrosynthesis from CO_2 and acetate. Our concept combines established technologies, emerging concepts, and new ideas into a novel integrated waste conversion process for the production of high-value biofuels and bioproducts. The new technology will be developed at the bench scale and demonstrated in the GasCube, a pilot-scale two-stage anaerobic digester at the South Dakota School of Mines & Technology. The project will demonstrate more than 25% improvement in both the levelized cost of energy production and the net levelized cost of disposal.

This multidisciplinary project is designed to achieve the project goal through four objectives: (1) enhance volatile fatty acids production in anaerobic digestion; (2) upgrade AD gaseous and liquid product streams; (3) evaluate and optimize the system to assess economic viability; and (4) integrate education with research. With a synergistic program of research and education, the project will help to educate the next generation of multidisciplinary researchers in innovative biological waste conversion solutions through partner organization activities involving university students, postdoctoral researchers, and the public. Funding from the Office of Energy Efficiency and Renewable Energy for this project will help develop this emerging wet-waste valorization technology, providing a more profitable alternative to biomethane from conventional anaerobic digestion.



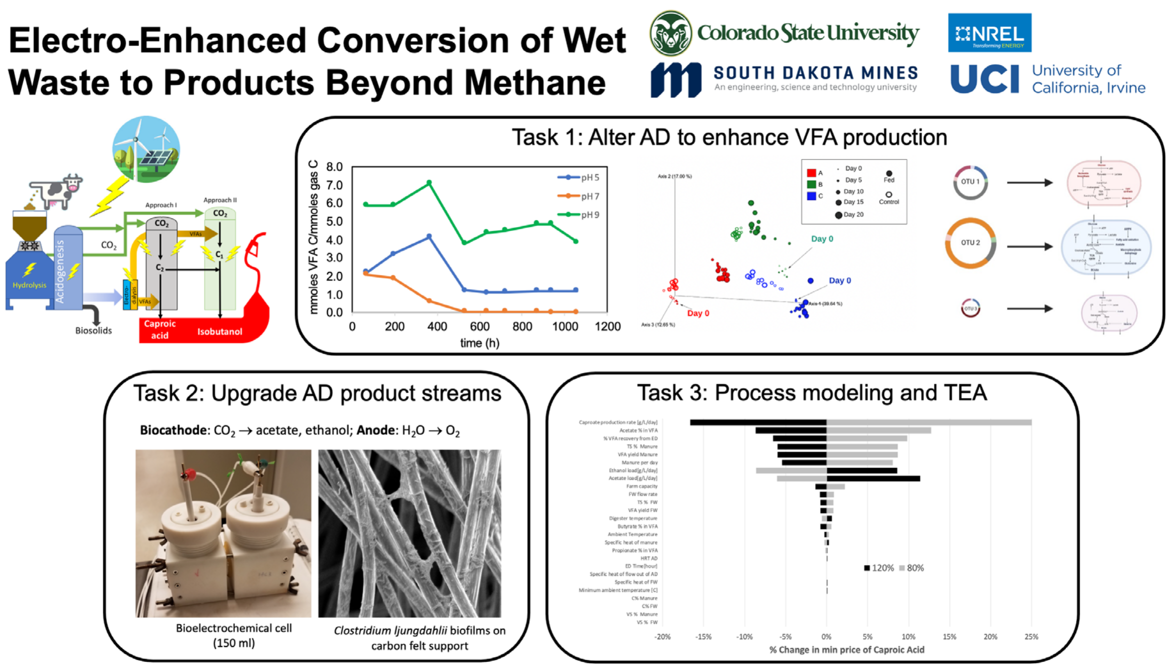


Photo courtesy of Colorado State University

COMMENTS

- Strengths: Sound method of communication between research partners (Colorado State University, University of California Irvine, NREL, and South Dakota School of Mines & Technology). Clear division of work and credible methods of data collaboration. Clear identification of commercial application of resulting products if research is successful. Demonstrates potential for significant regional and national impact (e.g., hexanoic acid to diesel precursor, isobutanol to gasoline blend). Strong merit in developing a process of CO_2 and VFA upgrade to caproic acid. Valuable education outreach component of the project for industry advancement and attraction of workforce professionals.

Weaknesses: The project would benefit from additional industry partners for commercial feedback on the technology development. The project would have valued from all partners being contractually activated simultaneously. Less has been performed than expected due to contractional conflict, which is detrimental to the research efforts achievable. Will be important to have a clear understanding the electricity consumption across these projects and how this impacts the commercial viability of this operational platform.

- The microbial electrosynthesis process has shown successful results. The electrodialysis process has not, and there was not discussion on the next steps involved with this process. Also would like to see more of a discussion on what impact pH and inoculum characteristics might have on the commercialization of this project. Additionally, I would like to see a mass balance and the proposed fate of the separated solids, including a discussion on potential of PFAS contamination. If there are any recycle streams to a WRRF, they should be identified and impact quantified.
- The project is very early-stage. The management plan appears to be well thought out and very comprehensive. The project is off to a solid start. It will be interesting to see as the results come in how many of the initial processes are cut versus improved and incorporated. The education plan is exciting and could have a broad impact, serving as a model for how to move the field forward in this space more dramatically. The various side streams and waste products should be considered and incorporated into the TEA/LCA.
- The research in this project is centered on exploring multiple potential pathways for both improving VFA production in arrested AD of waste and upgrading the VFAs to targeted final products. The management structure is adequate, though there is not a lot of discussion on specific risks and mitigation options for the pathways being investigated. The approach is clear, and the potential pathways being considered all appear to have significant potential, particularly those that will extend carbon chain lengths. The final target products of hexanoic acid (medium-chain fatty acid) and isobutanol (higher alcohol) are clearly identified and are relatively high-value chemicals compared to VFAs and biogas. However, there is a concern that too much is being attempted at once, with the risk being that they learn a little bit about everything rather than focusing funding resources on the one or two pathways considered most promising to maximize development. BETO will need to closely monitor progress, and a decision framework should be established to identify when and if either a clear leader among the various pathways emerges or it becomes evident that one will not be viable so as to redirect the maximum available resources to the most promising options. The proposed process involves multiple electrochemical steps, but there was no discussion on the anticipated energy demand or source of electricity, which could play a large role in determining commercial viability. Energy requirements should be assessed as early as possible both experimentally and within the TEA work. Task 1 results to date are interesting, although nothing was reported on two of the four options for arrested AD improvement in which the schedule indicates work was performed. Task 2 results and milestones are clearly presented, though no information was provided on bioconversion to alcohol work that the schedule indicates should have been started. The TEA work in Task 3 appears to be off to a good start, though the expected rate of MFSP improvement over the course of the project appears to be aggressive. By converting more carbon to more high-value chemical products than in conventional AD, this project is consistent with BETO’s goals and could have a substantial impact if successful.
- Very deliberate presentation of how the team is working together within tasks. Project is only really beginning, so a bit difficult to grade/rate this project. Was NREL doing any work? How much work was done at-risk? Trying to be fair to a project that was substantially impacted by COVID-19. Error bars in some of the charts, or was it only one test? Still very early in the project. Seem to have presented well the various dimensions and metrics for this project, which should give an accurate accounting of progress once time/conditions allow for work to be done. A fair bit of work on training students/researchers, seems a bit more National Science Foundation/Office of Science-y. While not

avoiding this activity, it may need to be reduced in favor of communication with the general public and the end market. Need to change the perception from waste as cost to waste as opportunity. May want to coordinate with NREL project 2.1.0.112 focused on technical assistance. Approach has a lot of pathways, and the team will need to be diligent in its downselect processes to make the best use of limited resources. Have created a preliminary tornado chart to show how different improvements impact the final sale price. Will be critical to show that the chosen limits are achievable by research and not just arbitrary metrics. Is the metric of −25% levelized cost of energy relevant to the market? Would be good to reconfirm to relate back to BETO's goals. BETO's overarching goal is to get technologies into the marketplace that valorize waste in large scales. This work is showing what is technically possible, but it's important to not lose sight of what is economically possible. There is significant potential for innovation and development in the research. I feel the scores on impact and progress are best judged as incompletes.

PI RESPONSE TO REVIEWER COMMENTS

- We thank the reviewers for their thoughtful comments and suggestions, and for making the effort to evaluate a project on which about 20% of the team has been funded for a year and the remainder for only about 3 months at the time of the presentation. The team is now making rapid progress. The project is also unusual in that the education and outreach component was specifically required by the funding opportunity announcement. We view this aspect as an important and high-impact contribution of the project, and it was rewarding to learn that two reviewers agree about this. Regarding the electrodialysis work, the progress has been good, and we view this as an important contributor to the overall technology. The TEA and LCA component of this project is tightly integrated with the experimental tasks, and the early model outputs have identified targets for the other tasks to achieve. All of the metrics used in the project are reflective of BETO's goals as specified in the funding opportunity announcement.

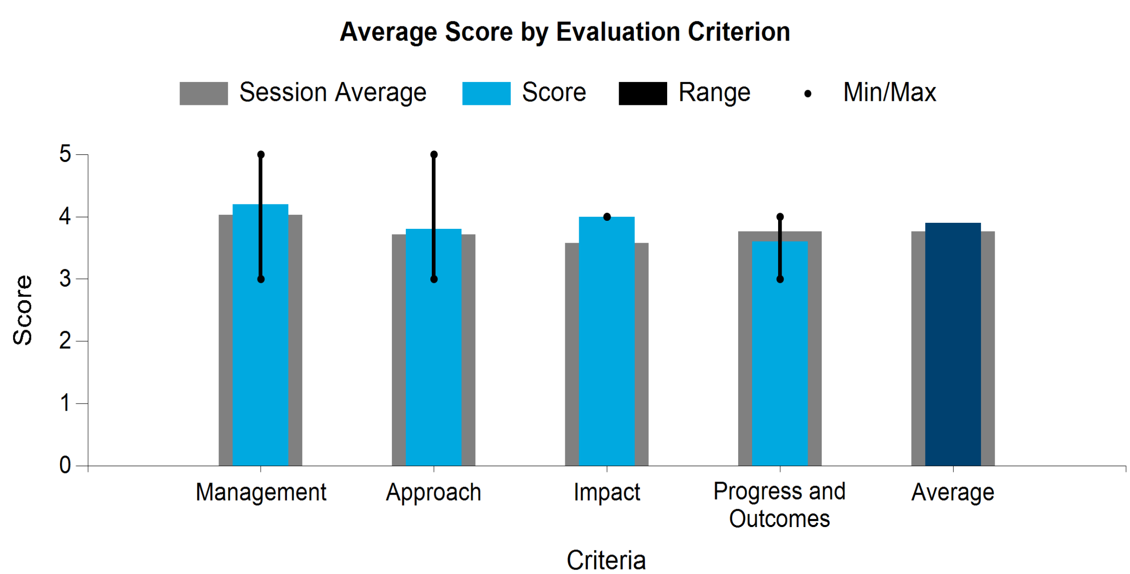
BIOMETHANATION TO UPGRADE BIOGAS TO PIPELINE-GRADE METHANE

National Renewable Energy Laboratory

PROJECT DESCRIPTION

WBS:	5.1.3.102
Presenter(s):	Adam Bratis; Kevin Harrison; Zia Abdullah; Courtney Payne; Jessica Krupa
Project Start Date:	10/01/2018
Planned Project End Date:	09/30/2021
Total DOE Funding:	$1,500,000

We are developing and de-risking a biomethanation process capable of megawatt-scale deployment that upgrades biogas waste streams to produce pipeline-quality RNG. Biomethanation is a two-step process using a methanogenic microorganism to convert renewable hydrogen (H_2) and waste CO_2 to renewable methane (CH_4)—the primary component in natural gas. Using biogenic CO_2 from biogas sources like dairies, wastewater treatment plants, and landfills allows production of this drop-in direct replacement fuel to participate in the growing number of carbon markets, like California's Low Carbon Fuel Standard and the federal Renewable Fuel Standard. The end-of-project goal is to demonstrate pipeline-quality RNG production (>95% CH_4, <4% H_2, <1% CO_2, <0.2% O_2, and <4-ppm hydrogen sulfide) using real biogas feedstocks. We will accomplish this goal by designing and building a pressurized (18-bar) mobile lab-scale (20-L) bioreactor research platform, including integrated electrolyzer system, based on lessons learned from operating the 700-L pilot system from Southern California Gas Company. In collaboration with Electrochaea, natural gas utilities, and Argonne National Lab, NREL will provide data to establish a preliminary range of carbon intensity to help accelerate the deployment of utility-scale H_2 production and qualify the biomethanation pathway process for RNG production from biogas sources.



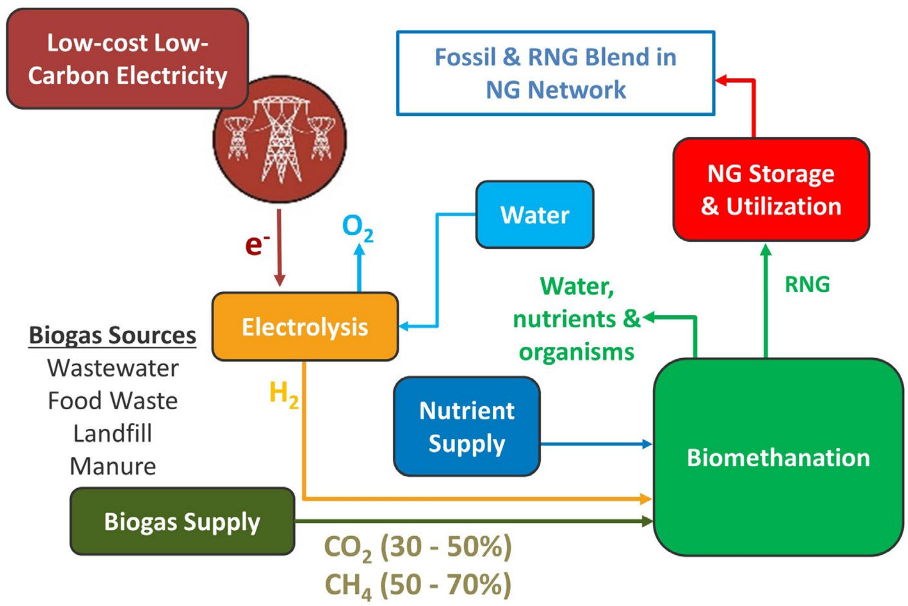


Photo courtesy of NREL

COMMENTS

- Clear eye to commercialization and field deployment of the system. Project has a strong and motivated industry partner in SoCalGas. Have a track record of working with this organization. SoCalGas is licensing the underlying intellectual property; clear pathway out of the lab and into practice. What does success look like in the field deployments of the pilot unit? Should NREL define success? Should the commercial partner define success? Am I missing something in pricing natural gas? Is $14 per million Btu worthwhile (read: commercially viable)? Significant regulatory credits are available. No Gantt chart or milestone chart was presented. Seems a bulk of the FY 2020 work was getting the mobile lab facility constructed. Was progress made on Task 1 about utility studies? The project appears quite worthwhile in a goal of producing RNG. Presenters were very helpful and responsive to the questions. Preliminary work on the 700-L unit seems very promising for load-following operations. What about real deployment and storage on site if the unit is not in operation? Great approach to reduce the size of RNG production and site the research equipment nearby to biogas production. Both the electrolyzer and the bioreactor can do load following. Better documenting the economic window in which this thing should operate, as well as the time regimes in which it works. May impinge on the aforementioned regulatory credits, which is necessary to make this make economic sense. Will be good for proof of concept. Needs to do better modeling to document performance at real-world scale. Highly resistant to other organisms invading because of its operational conditions. Organism is quite resilient. Electrochaea's strain is quite amazing.

- Good management plan. Data obtained to date look promising. Not sure how the archaea are retained in the process. Would like to see a discussion on organism retention, replacement, or sensitivity to changing conditions.

- Strengths: Good research and industry collaborations. Strong value-add partnership in SoCalGas. Clear value creation in upgrading biogas sources to pipeline-quality natural gas by leveraging abundant renewable energy and fermentation advancements. Clear demonstration of the technology's value creation to regional treatment facilities through regional case studies (e.g., Maine). Project on track to perform off-site technology demonstrations with custom trailer control room.

Weaknesses: Was difficult to determine the performance and challenges of the bioreactor activities due to lack of information in the presentation. More information on the impact of pressurized operation on the process economics and operational safety would have been valuable. Economics appear to be heavily dependent on cost of electricity. Would be valuable to identify near-term and long-term geographies these electricity prices will be attainable.

- The project management appears to be good with a strong team, solid expertise, and real input from utilities/industries in place. The presentation was very unclear, with progress and outcomes from other earlier projects described. The process itself was unclear. It seems that the main goal of this project is to both scale up and simultaneously scale down two existing systems. That seems to be moving forward. It will be important to see how contaminants in the gas affect the process and how well it functions at a larger scale at real sites. This looks very promising. The potential to use this kind of a system at landfills is also very exciting, but presents significant challenges regarding contaminants.
- This project intends to upgrade biogas to renewable natural gas through bioconversion of carbon dioxide to methane using hydrogen generated by electrolysis. Project management appears to be acceptable with smart inclusion of key industrial partners such as Electrochaea that should be able to help guide development, and SoCalGas that can enable implementation of the mobile version of the process by providing biogas sources. The proposed process, project approach, and tasks are clear from a top level, but the specific pathway to define success for each task along with task milestones are not obvious. For example, what exactly will be studied with respect to bioreactor gas mixing and microbe productivity in Task 2, and what needs to be improved? This project is unusual in that the reactor needs to be scaled down rather than up. It is also unusual that the two biggest stated cost drivers have to do with the electrolyzer, which does not appear to be part of the development work in this study. It should further be noted that based on the importance of electricity cost and the power that electrolysis typically requires, the process is unlikely to be viable without a dependable source of renewable energy. It seems like there should at least be an intermediate step where integrated operation can be verified technically and economically before moving to the field. Nevertheless, the deployment of a mobile system that can be taken to different biogas sources and tested is an important and innovative part of this project and an excellent idea to bring the technology directly to potential end users. Project results to date are interesting, but experimental data are limited due to the need to design and build the scaled-down bioreactor. A slide or two on specific future work would have been beneficial to understand how tasks 2, 3, and 4 will be implemented. If successful, the ability to reliably upgrade biogas to renewable natural gas using renewable hydrogen would have a significant impact on reducing carbon emissions and effectively improving digester yields.

PI RESPONSE TO REVIEWER COMMENTS

- A couple reviewers were unclear as to why we are scaling down while also pursuing scale-up for a demonstration facility. The 700-L (nominal working volume) bioreactor from SoCalGas was designed for pilot-scale operations at NREL with an electrolyzer having an electrical capacity in the range of 125 kW, which was the electrolyzer capacity that NREL was operating in 2014 (today it's 750 kW, with capability to 1 MW). Having about 250 gallons of culture (total) in the bioreactor vessel and balance of plant (e.g., pump, heat exchanger, piping) does not provide staff the flexibility to easily design and fund system modifications needed for research aimed at improving reactor design, reducing capital and operating cost, and gas mixing trials needed to increase hydrogen mass transfer. The scaled-down 20-L system provides a flexible mobile research platform that is more manageable for the types of trials needed to conduct advanced R&D in this two-step process: electrolysis plus biomethanation of waste to RNG. The end-of-project goal for this biopower project is upgrade real biogas to pipeline-quality RNG. The team considered bringing large quantities of compressed biogas from different sources to NREL, but decided a smaller, flexible research platform (that could also travel to actual biogas sources) was the more effective solution. The complementary electrolyzer/bioreactor integration project (WBS 2.3.2.700, CRD-19-00809) will also use this scaled-down platform to reduce to practice intellectual property developed at NREL and being licensed by SoCalGas. The ability to modify the smaller (18-kW) electrolyzer and 20-L bioreactor will provide a manageable platform for this work. This project is co-funded between BETO, SoCalGas, and the Hydrogen and Fuel Cell Technologies Office.

MODULAR MICROBIAL ELECTROMETHANOGENESIS FLOW REACTOR FOR BIOGAS UPGRADING

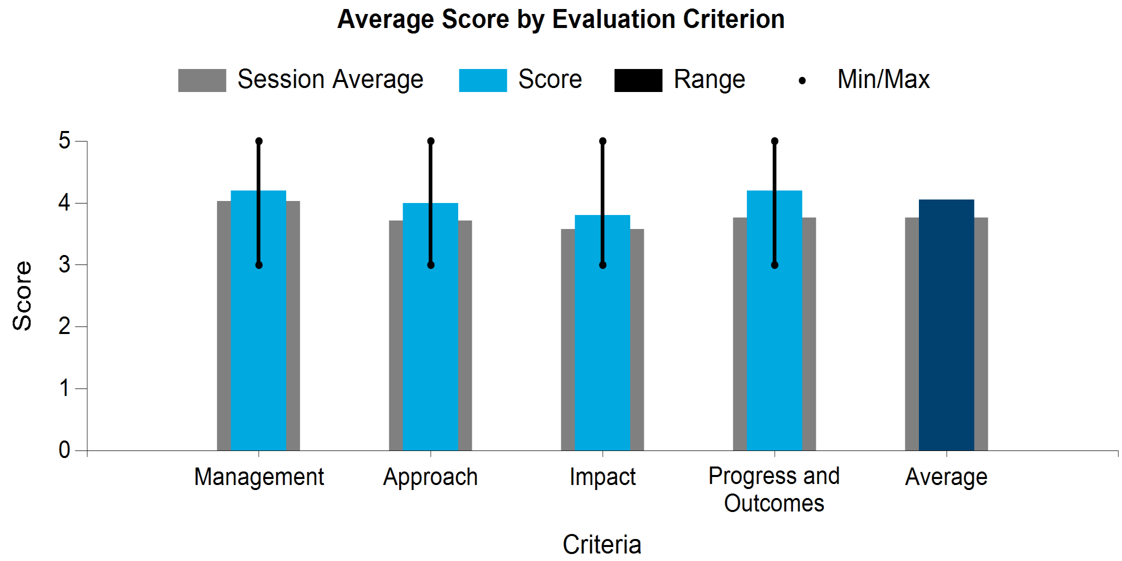
Lawrence Livermore National Laboratory

PROJECT DESCRIPTION

WBS:	5.1.3.104
Presenter(s):	Rhona Stuart; Sarah Baker; Dan Flowers
Project Start Date:	10/01/2018
Planned Project End Date:	09/30/2021
Total DOE Funding:	$800,000

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 methane 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 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 30 g/kWh, based upon a techno-economic assessment 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 techno-economic assessment of the technology for biogas upgrading and power-to-gas applications, paving the way for larger-scale demonstrations.



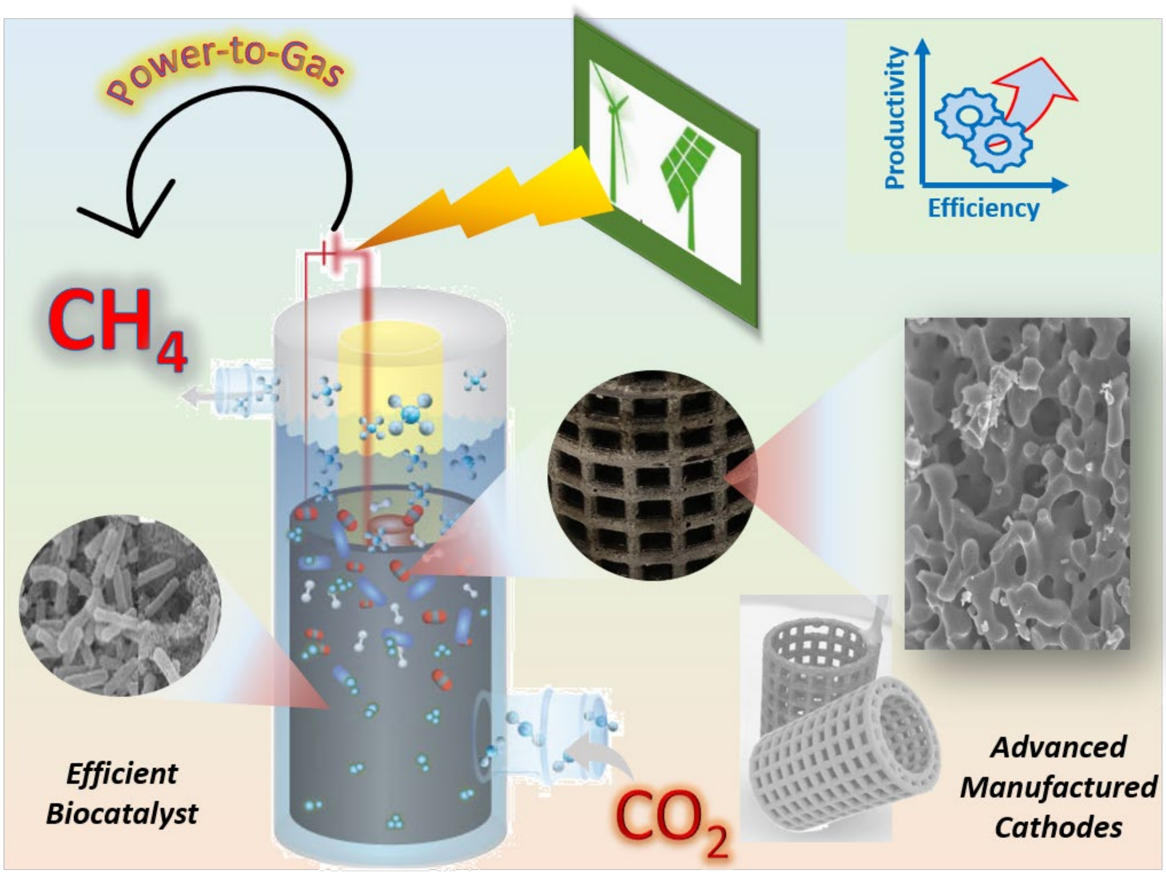


Photo courtesy of Lawrence Livermore National Laboratory

COMMENTS

- Could aluminum electrodes be used? Would reduce system weight. Is the test being run on biogas or pure CO_2 streams? Confirming resistance to impurities is going to be critical. Would this work for any CO_2 stream biogenic or non-biogenic? Stability to sulfur oxides and nitrogen oxides in feedstock CO_2 stream? This seems very exciting if it could potentially address energy storage problems associated with renewable energy by converting it into methane fuel. Clearly related to the goals of BETO. Team at Lawrence Livermore National Lab and Stanford appear to be communicating frequently and building off of each other's work. Overarching management of the project seemed a bit weak. Team appears to have made substantial progress along its milestones, and appears on track to hit its goals by June 2021. Good that an industry partner is engaged. Are they interested in commercializing? Would another entity be responsible for the technology operation? Assuming that the indicated purity goals meet the real rules on pipeline quality. I think there may already be appropriate (albeit limited) market conditions where something like this might already make sense. Could this be used to modify an existing natural gas power plant to turn it into an energy storage facility? Team has made substantial progress. Do any risk mitigation strategies need to be executed upon? At this point less looking for future strategies, but looking more to see what had to be executed upon. May want to get in touch with someone in the Office of Electricity. Lots of work on modeling the economics of energy storage. Q: How long is the ramp-up period to get to steady-state operation? A: ~30 days. What is causing the aberrations of gas output?

- Good management plan and project organization. Good progress toward milestones. Results to date show successes. In a typical AD process, a portion of the biogas is used to heat the incoming sludge/digester. Also, the cathode is operated at a higher-than-ambient temperature. Would like to see a discussion as to whether the uses of the biogas for heating impacts the economics of this process. Not sure how growth of the organisms and decay is managed. Also more discussion on surface area required at full-scale operation.

- Strengths: Effective methods of communication and collaboration were demonstrated between the research partners; strong value-add industrial partner in SoCalGas. Has valuable industry potential through electrolysis addition to existing digestors for pipeline-quality methane production. Novel advancement of cathode structure through 3D-printed matrix for advancement in surface area. Significant advancements have been made toward converting CO_2 into methane and demonstrating pipeline-grade methane concentrations under sustained operations.

  Weaknesses: It would have been valuable to discuss the challenges of scaling up the cathode and review what performance parameters may be impacted at larger scale (e.g., impacts on CO_2 conversion from operational changes or after prolonged operations). Additional industry partnerships for advice on challenges and limitations to commercializing microbial electrosynthesis would add value to this project. Was difficult to determine whether contamination of the microbial electrosynthesis culture would occur over time and how this would impact the product output.

- The focus of this project is on biogas upgrading using electromethanogenesis in a uniquely designed, single-stage reactor. The combination of an electrolysis unit for hydrogen production within a bioreactor vessel is highly innovative and a notable improvement over existing technology. The project has required good cooperation between biologists and electrode materials specialists to achieve the results presented. A discussion of risks that were overcome and challenges remaining would have been helpful to better understand current status. Specific tasks were not specified and the approach only presented from a top level, but the goals were nevertheless straightforward and clear. The results are impressive and the team appears to be on track to meet its milestones. A good description of the microbe choice and electrode design was provided. The methane concentrations achieved and long-term performance also appear to be good. On the downside, there was no discussion on the energy cost during operation, the reactor cost, or how easy it is to fabricate and operate the reactor and electrodes. The challenge will be in scaling up the design and making sure that reactions are not mass-transfer-limited with respect to hydrogen. In the remaining time for this project, it will be important to demonstrate equal performance with representative contaminants including siloxanes. Future work should also consider testing on power plant flue gas with sulfur oxide and nitrogen oxide contaminants, which could significantly expand the market for this technology if successful. The overall impact of this project is substantial, meets BETO's objectives, and appears to be a notable improvement over the current state of the art for biogas upgrading, but the ultimate scaled-up design must be proven to be economical and will likely require renewable electrical energy to be viable.

- The management appears to be very good. The project is early stage, in terms of development, and almost complete. The results are solid, but it is not clear what the end impact will be given the early stage, small scale, and the lack of data with real biogas. The work on the cathode and reactor should be transferrable to other projects. Overall nice job.

PI RESPONSE TO REVIEWER COMMENTS

- Thank you for your time and constructive reviews. We will test on simulated biogas containing H_2S. Definitely important to also test on raw biogas in the next stage of development. We agree, we are really interested in understanding techno-economic targets for energy storage, not just renewable gas production. We agree that scale-up while maintaining performance is a risk—in particular scaling to maintain mixing and transport across the membrane and cathode surface area. Additive manufacturing has been beneficial for us to rapidly prototype modular designs, but for full-scale reactors, we will need to adapt the designs for manufacturability.

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

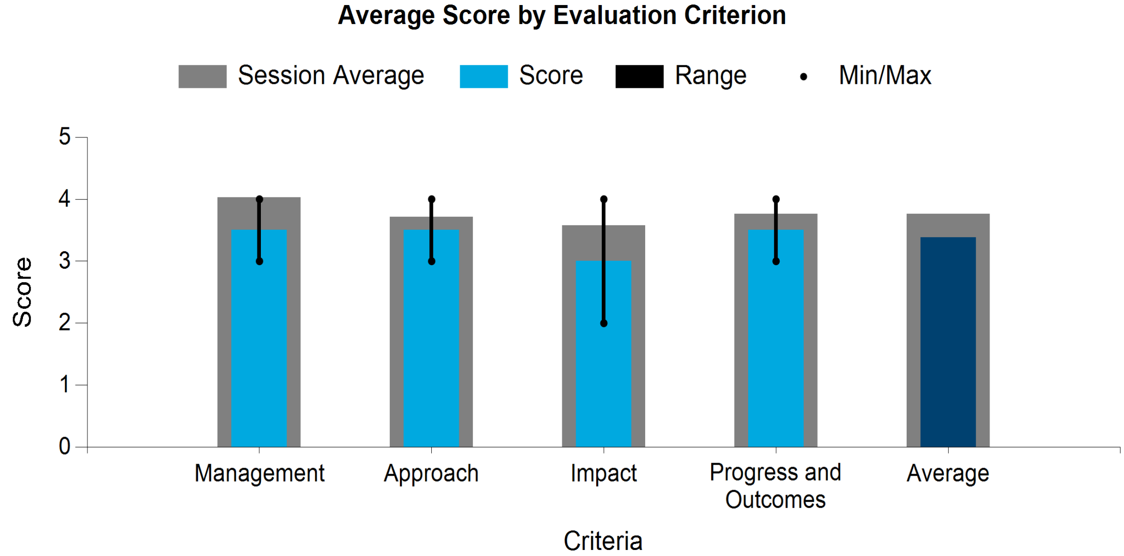
Argonne National Laboratory

PROJECT DESCRIPTION

WBS:	5.1.3.105
Presenter(s):	Meltem Urgun-Demirtas; Troy Hawkins
Project Start Date:	10/01/2018
Planned Project End Date:	09/30/2021
Total DOE Funding:	$1,500,000

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 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; AD capacity will likely increase in coming years. However, due to the economy of scale, biopower production for small scales currently is not economically feasible in the United States. Our ultimate aim is to develop a sustainable process that diverts organic fraction of MSW from landfills and incineration while generating renewable energy and capturing nutrients to meet the demands of organic waste generators and hauling companies.

The objective of this project is to improve the techno-economic viability of biopower production by developing a sustainable two-stage AnMBR system that diverts the organic fraction of MSW from landfills and incineration while generating methane and renewable bioproducts. To achieve this goal, the 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; (2) develop a first-stage AnMBR inspired by the stomach physiology of ruminants that enhances hydrolysis and acidogenesis to maximize VFA production; (3) develop a second-stage AnMBR that exploits biofilm growth to enhance methanogenesis and maximize the conversion of VFAs to methane; (4) perform process simulation and analysis to model full-scale performance of new AnMBR technology, and (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 the full scale.



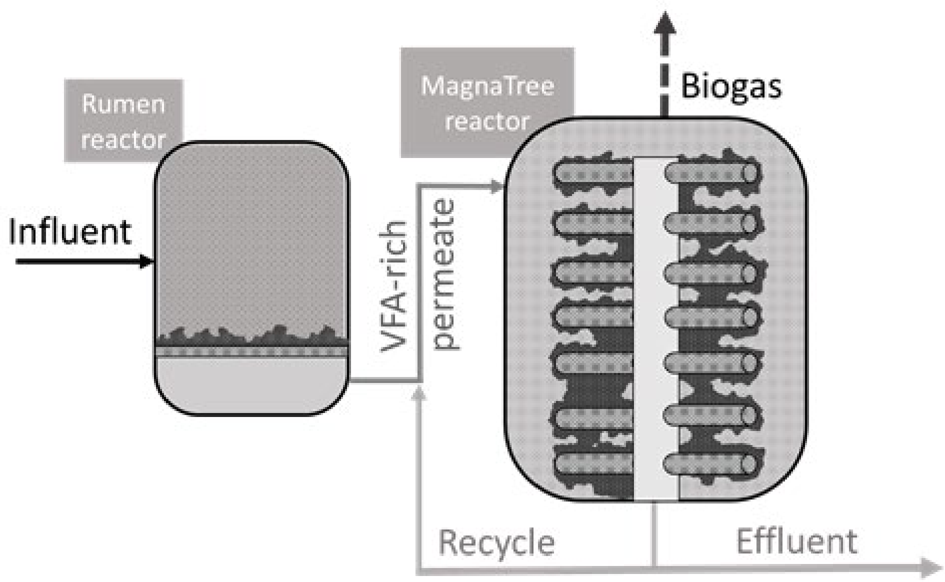


Photo courtesy of Argonne National Laboratory

COMMENTS

- Management plan is identified and seems to be adequate. Risks and risk mitigation strategies were not identified. Would like to see a material balance on this process, solids, COD, and nitrogen species. Concerns include the quantity of rumen solids produced and the projected disposal. They have achieved significant COD reduction, but would like the volatile solids reduction rate also quantified. Also concern about the long-term efficiency of the MagnaTree; my understanding is that it relies on conversion in the biofilm. With time, the biofilm thickness will increase, and that might reduce conversion rates. Would like to see a mass balance and a discussion on disposal options/issues associated with the two waste sludges. Also a discussion on any recycle streams to the WRRF and potential impact.

- Project seems well positioned to high the target methane yield, having most recently achieved a value of about 90% of the final target value. Team seems to have a good track record through the project of working together. Regular meetings have engaged industry partners. Have there been any specific or tangible contributions they have provided to the team? Risk plan is minimal, although this project is substantially advanced. Perhaps instead look a bit more retrospectively about how risk mitigation strategies were put into action? Have done outreach at industry and academic functions. One of the industry partners seems interested in commercializing, but still very early in its commercialization journey. LCA/TEA slides became a bit of an eye test to understand. Call out key findings. Outcomes become more important over process as you look to transition out of an academic setting. Team appeared to have a strong technical approach to the problems of this project. It is good that they have opened up some of their modeling work to be accessible to others via GitHub. Still a bit difficult to understand the broader impact of the metrics that the team hit (as noted in one of the previous comments). The team did address the motivation piece. Optimization of two unit operations in separate reactors is ideal, but does come with concomitant increase in CapEx. Q: What is the pathway from here/the endpoint? A: Looking at larger scales. May want to pause and do some modeling to show economic feasibility at larger scales and sensitivity to some of the critical factors. Process is not inherently responsive to feedstock variability. Able to modify process, but would need sensors to characterize the feedstock, or would need greater control of the feed.

- Strengths: Good research management plan between Argonne National Laboratory and University of Michigan. Have value-add relationships with Gray Brothers, RAE, and MWRD. Significant reduction in global warming potential if project is successful. Strong impact potential from the project if successful due to enhancing methane production in anaerobic digestion through in situ membrane addition. The ability to work with feedstock flexibility will be highly relevant when the technology is applied to regional digestions platforms.

  Weaknesses: The project would value from partnerships with commercialization/scale-up partners. It was difficult to understand whether the increased capital cost for the membrane system and/or the increased electricity consumption would still enable the technology platform to be commercially viable. The digestion work is currently operational in batch mode. There are signification operating challenges that arise when transitioning from batch to continuous operation. The project will value from transitioning to continuous operation as soon as possible. The project would value from running a control reactor in parallel in order to baseline the digestion outcomes.

- The focus of this project is to explore various improvements to the AD process with wet-waste feedstock for increasing methane yield using a novel two-phase AnMBR. The project management appears to be adequate, though there is not much discussion of specific risks and mitigations associated with the project. The approach is clear and well organized. The presentation of the main achievement of higher methane yield relative to contemporary studies, along with a relatively higher load rate and shorter retention time, is clear and a significant achievement. However, it is unclear how the additional claim of a twofold reduction in AD footprint was achieved. The use of microbes from the bovine rumen for improving initial AD reactions seems incredibly simple yet innovative and effective based on the results presented (almost begging the question of why this wasn't thought of sooner). Likewise, the relatively simple increase in pore size in the second-stage membrane reactor that allows less expensive membrane material and less frequent fouling appears to be a notable accomplishment. It is not clear, however, if the integrated process has ever been tested, which is critical to assessing the potential commercial viability. Also, other than stating that the pilot-scale experiments started in February 2021, there was no further information provided about these tests, their objectives, and whether there is sufficient time left in the project (slated to end in September 2021) to achieve meaningful results. Model improvements are encouraging and a welcome sight to see that it has entered the public domain. The project impact is moderate; while it improves existing AD technology and the focus on small-scale applications is important, the end product of biogas is still a relatively low-value product.

PI RESPONSE TO REVIEWER COMMENTS

- The project team would like to sincerely thank the reviewers, who took time and effort to provide us with constructive comments and valuable feedback for this project. We have addressed their comments, and below are itemized responses to each of the weakness queries of the reviewers.

- Reviewer #1 Comments: "The project would value from partnerships with commercialization/scale-up partners." The project team has already reached out to industry to scale up the process. For example, we have been partnering with Carollo Engineers Inc., InCTRL Solutions Inc., Great Lakes Water Authority, and Metropolitan Water Reclamation District of Greater Chicago in a recent BETO-funded project to scale up the process. The project team has been also partnered with Brown & Coldwell in response to recent funding opportunities from the Advanced Research Projects Agency–Energy and BETO.

  "It was difficult to understand whether the increased capital cost for the membrane system and/or the increased electricity consumption would still enable the technology platform to be commercially viable. The digestion work is currently being operational in batch mode. There are signification operating challenges that arise when transitioning from batch to continuous operation. The project will value from transitioning to continuous operation as soon as possible. The project would value from running a control reactor in parallel in order to baseline the digestion outcomes." The project team respectfully disagrees with the reviewer's comment. Slide 14 includes the results from the long-term continuous operation of the MagnaTree reactor at bench scale, which achieved a high methane yield (average 0.55-L/g volatile solids compared to literature data of 0.4-L/g volatile solids) and a high COD removal rate (average 84% COD removal). Since there are abundant data available on stand-alone food waste digesters used for biogas production at field scale, we have been comparing our results with the available literature data as control.

- Reviewer # 2 Comments: "Have there been any specific or tangible contributions they have provided to the team?" Yes, InCTRL Solutions Inc. helped us conduct techno-economic analysis. Both MWRD and InCTRL helped us in designing scale-up studies to be conducted in a newly funded project.

  "Risk plan is minimal, although this project is substantially advanced. Perhaps instead look a bit more retrospectively about how risk mitigation strategies were put into action?" Since food waste consists of food items with highly varying digestibility, clogging of the supporting mesh of the dynamic membrane by the recalcitrant materials in food waste, such as lignin at a high through-membrane flux was a risk. To overcome this risk, we increased membrane surface area to decrease the through-membrane flux, therefore reducing the risk of clogging. Instead of running two-phase reactors together, we run individual reactors. This operation plan helped us identify risk points, improve reactor design, and determine the optimal operating conditions. In current integrated operation, the potential risk is that the second stage relies on the effluent from the first-stage reactor. Although the first-stage reactor is more resilient than the second-stage reactor, should a system failure occur in the first stage, the second-stage reactor will not be receiving the appropriate feed to which it has acclimated. To overcome this risk, we have been storing excessive first-stage effluent as the emergency feed to the second-stage reactor.

  "Have done outreach at industry and academic functions. One of the industry partners seems interested in commercializing, but still very early in its commercialization journey." The project team has already reached out to the industry to scale up the process. For example, we have been partnering with Carollo Engineers Inc., InCTRL Solutions Inc., Great Lakes Water Authority, Metropolitan Water Reclamation District of Greater Chicago, and universities in North America (University of Toronto, Universidad Nacional Autónoma de Mexico Tecnológico de Monterrey) in a recent BETO-funded project to scale up the process. The project team has also partnered with Brown & Coldwell in response to recent funding opportunities from the Advanced Research Projects Agency–Energy and BETO. The project team has been publishing and presenting the outcomes of the project in journals and conferences, respectively. We are currently working with the external collaborators from Lund University, who are also the original developers of the Anaerobic Digestion Model No. 1 (ADM1) model. We will publish our version of the model along with other versions of the model listed in the GitHub repo. Publishing our model at the wwtmodels repo should significantly increase the visibility of our model.

“LCA/TEA slides became a bit of an eye test to understand. Call out key findings. Outcomes become more important over process as you look to transition out of an academic setting. Team appeared to have a strong technical approach to the problems of this project. It is good that they have opened up some of their modeling work to be accessible to others via GitHub. Still a bit difficult to understand the broader impact of the metrics that the team hit (as noted in one of the previous comments).” The project goals are the development of a scalable, high-performance, low-cost, two-phase modular AnMBR (30 liters) by improving reaction kinetics (reduce digestion time from 5–10 days to 12–48 h) and increasing methane yield (0.45-L/g volatile solids fed) to reduce footprint and operating cost of biogas production. With the rumen and MagnaTree two-phase reactors, we were able to reduce digestion time to 0.5 days and 4.7 days, respectively, compared to 10–20 days of conventional AD operations.

“The team did address the motivation piece. Optimization of two unit operations in separate reactors is ideal, but does come with concomitant increase in CapEx.” We agreed; an increase in number of unit operations increases CapEx. With the rumen and MagnaTree two-phase reactors, we were able to reduce digestion time to 0.5 days and 4.7 days, respectively. New AD configuration improved reaction kinetics, hence reducing the required AD footprint by 2–4 times (when total, 5 days of operation compared to 10–20 days of conventional AD operations) and increased methane yield (0.55-L/g volatile solids fed compared to 0.4-L/g volatile solids), hence reducing the cost of biogas production.

“Q: What is the pathway from here/the endpoint? A: Looking at larger scales.” Our final deliverable in this project is to scale up the technology to a 36-liter reactor. The project team will further scale up the technology with new funding.

“May want to pause and do some modeling to show economic feasibility at larger scales and sensitivity to some of the critical factors.” Techno-economic analysis was conducted with different plant sizes to determine the critical factors.

“Process is not inherently responsive to feedstock variability. Able to modify process, but would need sensors to characterize the feedstock, or would need greater control of the feed.” Fluctuations in VFA and methane productions are due to (1) at lab-scale small reactors, the reactor geometry is a limiting factor in the mass transfer and control of digester. Large-scale fermenters will eliminate most of these issues. (2) When these limitations coupled with feedstock variability (composition and digestibility), the system performance showed the fluctuations in terms of methane yield. It should be noted that the digesters were fed based on volatile solids loading rate, but not organic carbon content. Even though the same solid loading rate was used during the experiments, variations in feedstock composition resulted in different organic carbon content and digestibility in the feedstock fed to the system. As shown in Slide 14, the COD removal performance was mostly constant (average 85% removal) even with variations in feedstock, hence showing robust digester operations.

Reviewer #3 Comments: “Management plan is identified and seems to be adequate. Risks and risk mitigation strategies were not identified.” Since food waste consists of food items with highly varying digestibility, anaerobic biodegradation of recalcitrant materials, such as lignin at high organic loading rates, was a risk. To overcome this risk, we increased membrane surface area to increase the digestibility of recalcitrant materials. Instead of running two-phase reactors together, we run individual reactors. This operation plan helped us identify risk points, improve reactor design, and determine the optimal operating conditions.

“Would like to see a material balance on this process, solids, COD, and nitrogen species. Concerns include the quantity of rumen solids produced and the projected disposal.” We conducted a mass balance on the integrated two-phase rumen and MagnaTree reactor. Currently, overall volatile solids removal is 50%. It should be noted that the MagnaTree reactor hasn't reached steady state, and overall volatile solids removal is expected to increase when the system reaches steady state. Both TEA and LCA frameworks considered the treatment and disposal of the leftover solids (i.e., sludge treatment). TEA also considered the recycle streams.

"They have achieved significant COD reduction, but would like the volatile solids reduction rate also quantified." The volatile solids reduction was addressed in the previous response.

"Also concern about the long-term efficiency of the MagnaTree; my understanding is that it relies on conversion in the biofilm. With time, the biofilm thickness will increase, and that might reduce conversion rates." MagnaTree operations mainly rely on convectional mass transfer (membrane flux), while the diffusivity has a limited impact on the performance. Clean in place (periodic membrane cleaning) will also take place to maintain the permanent membrane flux; hence, this periodic cleaning will also help to maintain biofilm thickness constant within the membrane reactor.

"Would like to see a mass balance and a discussion on disposal options/issues associated with the two waste sludges. Also a discussion on any recycle streams to the WRRF and potential impact." Both TEA and LCA frameworks considered the treatment and disposal of the leftover solids (i.e., sludge treatment). Slide 20 – TEA Framework, Residual management (line 3 in Cost & Revenues figure) specifically showed its impact. Slide 21 – LCA-System boundary figure shows the waste disposal associated options and their impact was analyzed by environmental analysis considering their global warming potential, acidification, eutrophication, smog, and respiratory impacts.

Reviewer #4 Comments: "The project management appears to be adequate, though there is not much discussion of specific risks and mitigations associated with the project." Since food waste consists of food items with highly varying digestibility, anaerobic biodegradation of recalcitrant materials, such as lignin at high organic loading rates, was a risk. To overcome this risk, we increased membrane surface area to increase the digestibility of recalcitrant materials. Instead of running two-phase reactors together, we run individual reactors. This operation plan helped us identify risk points, improve reactor design, and determine the optimal operating conditions.

"However, it is unclear how the additional claim of a twofold reduction in AD footprint was achieved." With the rumen and MagnaTree two-phase reactors, we were able to reduce digestion time to 0.5 days and 4.7 days, respectively. New AD configuration improved reaction kinetics, hence reducing the required AD footprint by 2–4 times (when total, 5 days of operation compared to 10–20 days of conventional AD operations) and increased methane yield (0.55-L/g volatile solids fed compared to 0.4-L/g volatile solids), hence reducing the cost of biogas production.

"It is not clear, however, if the integrated process has ever been tested, which is critical to assessing the potential commercial viability. Also, other than stating that the pilot-scale experiments started in February 2021, there was no further information provided about these tests, their objectives, and whether there is sufficient time left in the project (slated to end in September 2021) to achieve meaningful results." The slide deck for the Peer Review was submitted to BETO on February 19, 2021. The scale-up studies started at the end of February. The two-phase system started up with a 6-L first-phase rumen reactor and a 43-L second-phase MagnaTree reactor using rumen content and digestate from full-scale acid-phase digester treating municipal sludge and food waste as the inoculum for the first phase, and a full-scale second-phase digester digestate as the inoculum for the MagnaTree reactor. A mixture of pre-consumer and post-consumer food has been used as a feedstock. The first-phase reactor had an average hydraulic retention time of 12 hours, while the second phase had a 5-day hydraulic retention time. The solids retention time for the first-phase rumen reactor was controlled to be around 5 days by wasting the bulk solution digestate, while the solids retention time of the second-phase MagnaTree reactor was not controlled but was only determined by the solids content in the only-liquid output from the reactor. The rumen reactor quickly reached and exceeded our VFA yield target of 0.35 kg VFA/kg volatile solids fed within 3 weeks after startup. We met and exceeded the milestone for FY 2021 Q2 and the first-phase reactor. The effluent from the first-phase rumen reactor was fed to the second-phase MagnaTree reactor. The second phase was started up on day 21 and it has been still in the transition phase. Currently, an average COD reduction in MagnaTree reactor is 61%. The initial results showed the scalability of the two-phase reactor. Our next step is to optimize operating conditions to meet the target to "produce methane at a yield of 0.45-L/g volatile solids fed in two-phase AnMBR (36 liters) on a sustainable basis at technology readiness level 4" set for this project by the end of September 2021.

"Model improvements are encouraging and a welcome sight to see that it has entered the public domain. The project impact is moderate; while it improves existing AD technology and the focus on small-scale applications is important, the end product of biogas is still a relatively low-value product." The project was in response to a BETO lab call on biopower production, which also required the development of new biogas production technologies.

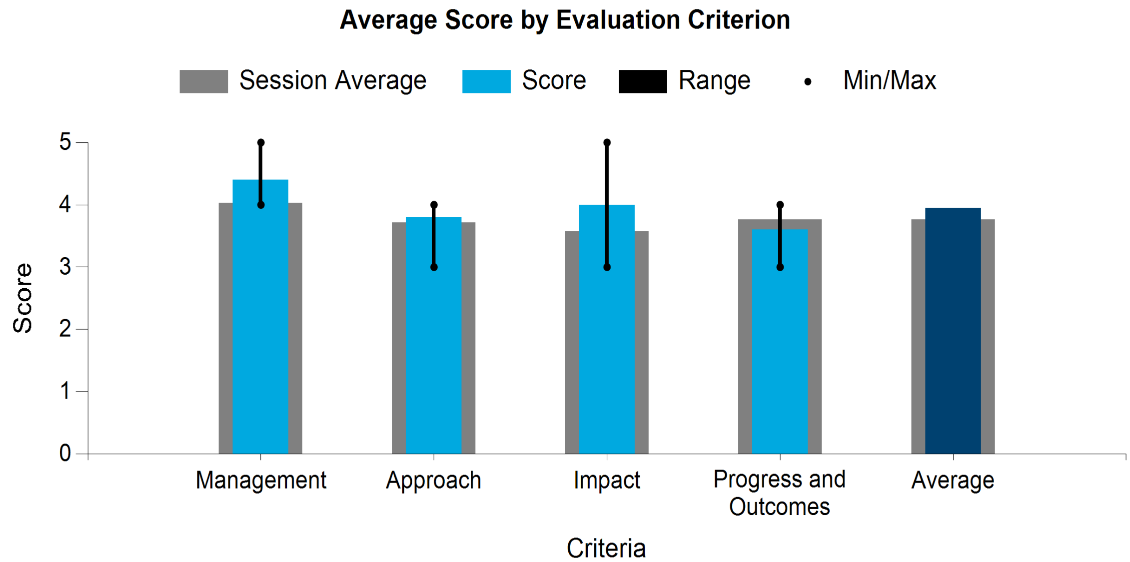
MAXIMIZING BIO-RENEWABLE ENERGY FROM WET WASTES (M-BREWW)

University of Illinois at Urbana-Champaign

PROJECT DESCRIPTION

WBS:	5.1.3.201
Presenter(s):	Lance Schideman
Project Start Date:	10/01/2018
Planned Project End Date:	12/31/2022
Total DOE Funding:	$1,585,115

Municipal wastewater treatment plants consume up to 3% of total U.S. electricity demand, and typical electrical costs account for about 40% of their annual operating budget. These facts are related to the prevailing use of conventional activated sludge processes for aerobic degradation of wastewater organics into CO_2, which dissipates the organic energy content of wastewater and requires a large aeration energy input. This project aims to enhance biopower recovery from municipal wastewater organics through development of a novel cloth-filter AnMBR combined with ammonia ion-exchange and ammonia electrolysis. Together, this three-part system will maximize the conversion of wastewater biosolids and ammonia into two harvestable fuels: methane and hydrogen gas, which can be co-combusted for electricity production. This novel system has the potential to increase the net energy recovery from wastewater by more than 10-fold by eliminating the energy input for aeration, decreasing the energy needed for AnMBR fouling control, and increasing the fraction of energy harvested from wastewater organics. This project includes lab-scale work for optimization of the unit process components, and then pilot-scale demonstration at an operating wastewater treatment plant. Thus far, the novel cloth filter AnMBR has been operated at pilot-scale for over a year and achieved a very low energy demand of 0.009 kWh/m^3 for fouling control, which is 97% lower than the average values reported for other pilot AnMBRs. The observed tradeoff was reduced effluent water quality in terms of COD removal efficiency (66%) and effluent TSS concentration (29 mg/L) when compared to conventional AnMBRs. However, it was further demonstrated that by adding an in-line coagulation-flocculation process, the cloth filter AnMBR performance could provide effluent water quality comparable to the baseline conventional activated sludge process. In the next phase of the project we will install and operate the optimized ammonia ion-exchange and electrolysis processes into the pilot-scale operations for demonstration of the fully integrated wastewater treatment system.



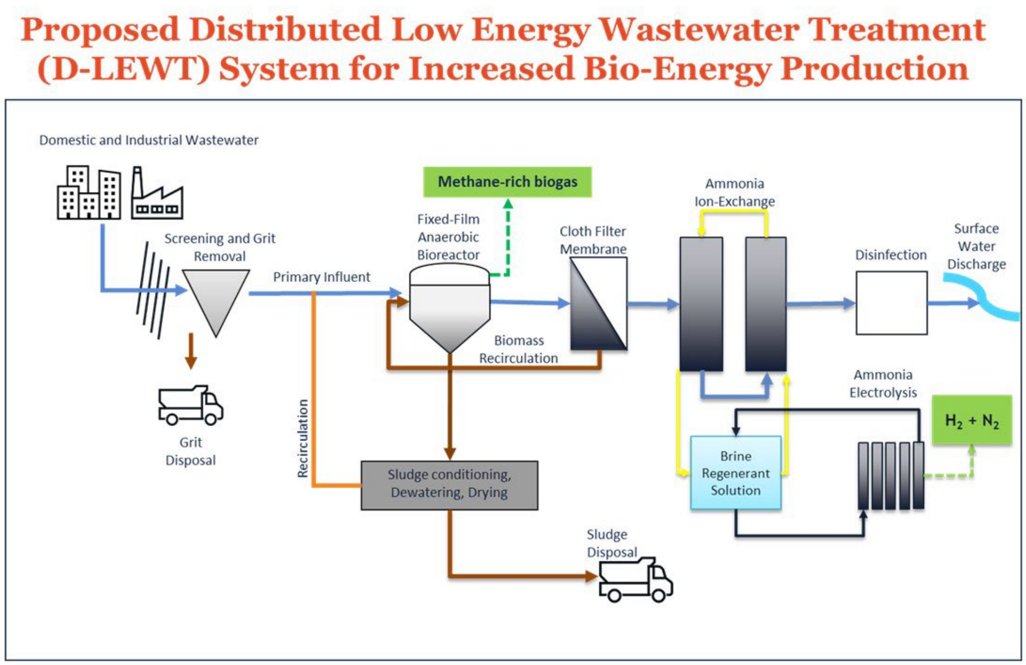


Photo courtesy of University of Illinois at Urbana-Champaign

COMMENTS

- Management plan is very good, and they have identified the risk and risk mitigation strategies. Would like to see a material balance and a nitrogen species balance (especially soluble organic nitrogen). The concern is the total nitrogen exiting the process. Many WRRFs have very low total nitrogen permit limits, including seasonal ammonia limits of 1 mg/L. The cost of disposal for the waste sludge need to be quantified, and the expected disposal option should be identified. There should be a discussion on the life of the ion-exchange resin and the fate of the spent resin.

- Project seems to be making great progress, as it is about halfway along. Were there any impacts to the project's schedule from COVID-19? Tackling of big issues involved in operating a wastewater treatment plant: aeration and N control. Seem to be well along their way in meeting their process goals of having lower process costs as compared to conventional activated sludge/AD. Conventional activated sludge/AD is a good baseline. Would have been good to have intermediate goals to check that progress is tracking with expected. Clear performance over the initial baseline case for this system. Using more porous membranes results in greater flow, and less energy spent addressing the challenge of membrane fouling. Aqua-Aerobics is experienced in the water space and clearly invested in getting more applications into the space (motivated partner). Ambreon is scaling up the ammonia electrolysis technology—so both parts are looking to transition into the real world. Team appears to be communicating frequently and effectively. Risk mitigation strategies are in place. Unclear which, if any, have been put into practice. Really nice work on the improved flow dynamics of the ammonia electrolysis cell. Do need better separation of the H_2 from the N_2 column. What, if any, are the concerns of excess N_2 in the H_2 column? Nitrogen oxide emissions? If these are manually switched, how would this be scaled? Where do you expect to be able to get to in terms of separation/where do you need to get to? The additional chemicals/NaOH impact on cost and LCA was discovered late; should reflect this challenge in an updated risk register.

- Strengths: Well-constructed project team with research facilities, engineering firms, and industry partners all actively engaged. Clear approach for capturing more carbon from the feedstock and upgrading it to methane for power generation through lower-cost cloth membrane applications. Novel approach for the inclusion of ammonia recovery and electrolysis for hydrogen gas production. Have de-risked the cloth filter use by leveraging wastewater treatment experience in cloth polishing applications. Preliminary electricity balance suggests significant value creation for wastewater treatment plans if these technology innovations come to fruition.

  Weaknesses: A number of the risks were identified as low-risk (e.g., brine recirculation in electrolysis process, contaminant challenges in membrane processes). These should be monitored carefully, as these risks appear to be higher than identified. Hydrogen gas will have higher-value applications in hydrogen cells. The team is encouraged to look for opportunities to divert and test this hydrogen production for this application (e.g., transportation). Will need to address the dissolved methane content, which is currently 50% of total production. More information on how the membrane unit and the electrolysis system would be integrated into an existing anaerobic digestion platform would have been helpful.

- The management plan is clear and well thought out. The project is complex, and there are a number of places where alternatives could be considered (using the NH_3 directly rather than sending it through electrolysis, burning the H_2, CH_4, and residual NH_3 [without a high-purity target], using the H_2 for a higher-quality end product rather than combusting it, etc.). It would be a good idea for the PIs to explore these options at least in the TEA and LCA to provide multiple paths forward. The project was well presented and the results and progress are clear and look promising. Integration and reduced chemical use will be the challenge. The potential need for post-treatment is a risk, as is the high quantity of dissolved CH_4 in the AnMBR effluent. These also should be addressed clearly in the TEA and LCA (they do not currently appear to be incorporated), and plans for mitigation should be incorporated.

- The project proposes an alternative process to conventional two-stage wastewater treatment using an AnMBR for direct digestion of wastewater along with nitrogen treatment. There is a good upfront quantitative description of the proposed distributed low-energy wastewater treatment (D-LEWT) process compared to the conventional wastewater treatment process, along with detailed advantages and disadvantages of the use of the AnMBR. The management looks good, with smart inclusion of wastewater industry stakeholders and industry partners that specialize in key components of the process. The approach is clearly presented. The use of large pores and cloth material for the membrane as the key to improved performance appears to be very similar to the Argonne-led project in this session, prompting a question of whether there is a duplication of efforts, although the current project's use of a single-stage rather than two-stage AnMBR is a clear advantage. The nitrogen control steps (ion exchange and electrolysis) are an important inclusion, and their value, if successful, is considerable, but relatively little information is provided to assess how efficient (with respect to yields and energy cost) and practical this part of the process is. The AnMBR results presented are encouraging, but it is unclear whether the biogas produced (>130 mL CH_4/g COD) meets the 85% COD value for biogas specified in the process description. Relatively few results are presented for a project about halfway to completion, and no results are presented on the ion exchange work. An important part of this project will be the integrated pilot-scale tests still to come, but there was no discussion of this aspect of the project. The TEA and LCA results are very informative. The TEA project goal shows a significant cost improvement compared to the baseline AnMBR design, but curiously shows only a slight reduction relative to conventional wastewater treatment processes, which appears to be due to a notably higher chemical and overall CapEx cost. The production of more biogas and hydrogen while removing nitrogen in the D-LEWT process is a significant improvement over conventional wastewater treatment, but the limited improvement in overall cost and the fact that the product biogas is still relatively low in value reduces the magnitude of its impact.

PI RESPONSE TO REVIEWER COMMENTS

- Thanks to all the reviewers for your encouragement and constructive criticism on this project. The paragraphs below provide a response to selected issues raised by the reviewers, with more of a focus on perceived weaknesses, areas where some additional clarification was needed, and potential changes to the project approach. First, the issue is numbered, summarized, and then our response is provided. The sequence of issues generally follows the order of comments provided in the BETO Project Peer Review system, but some similar and related issues are grouped together at their first occurrence.

  1. Were there any impacts to the project's schedule from COVID-19? There were impacts on the project work and schedule due to COVID-19 mitigations that began with lockdowns from March–July 2020, and these impacts continue to a lesser degree with reduced lab occupancy limits and extended delivery times for certain supplies. To date, we have been able to meet all the project milestones, but COVID-19-related delays have reduced the amount of process optimization on certain project aspects, mostly related to the ammonia ion-exchange and electrolysis processes. Thus, we have recently decided to request a 6-month no-cost extension for the current budget period (BP2), which would change the BP2 completion date from June 30, 2021, to December 31, 2021, if the extension is granted and fully exercised. This extension will enable the project to mitigate the delays associated with COVID-19.

  2. Would have been good to have intermediate goals to check that progress is tracking with expectations. We have interim performance milestones to track the progress of the project and go/no-go criteria at the end of each budget period. In addition, we are continuously tracking our experimental research impacts through concurrent TEA and LCA modeling of the treatment process alternatives, which is also used for refining experimental plans to focus on high-impact topics. Current TEA and LCA progress is being tracked in reference to the final project goals and in comparison to two reference baseline cases: one for conventional activated sludge with side-stream anaerobic digestion and a second baseline case for mainstream AnMBRs using system performance parameters as of the start of this project. Finally, our general progress is monitored through DOE quarterly reports, monthly internal team meetings, and bimonthly review meetings with DOE program managers.

  3. Various questions related to the separation of the gases H_2 and N_2 after NH_3 electrolysis and higher-value uses of H_2 (e.g., transportation fuel). N_2 does not necessarily need to be separated from H_2 after electrolysis when the intent is to co-combust the H_2 with the CH_4 in biogas. Without separation, the N_2 in the combustion process would be somewhat higher, which may lead to greater nitrogen oxide emissions. However, there is already a large amount of N_2 in the combustion process from the combustion air supply, and thus the resulting increase in nitrogen oxides may be trivial. We plan to conduct combustion

tests with elevated N_2 levels associated with not separating the N_2 and H_2 from electrolysis to quantify the effect on nitrogen oxide emissions. We have recognized the additional value of separating the H_2 for other uses, and we have included that in our TEA modeling as “displaced hydrogen,” which is valued at $10/kg. Despite the economic advantages of diverting H_2 to other uses, many wastewater plant operators may be leery of the reliability or extra effort required to manage H_2 offtake contracts. Thus, an option to burn H_2 directly on-site for power production is still a relevant alternative. If H_2 is to be used for vehicles or bottled gas supplies in existing markets, the removal of nitrogen will likely be required to increase H_2 purity to above 99%. For conventional hydrogen production from steam methane reformation, polishing processes are added after reforming to increase hydrogen purity, and these could also be added after our electrolysis process. For this project, we set an H_2 purity goal of >93% to demonstrate significant progress on purity metrics, and we also plan to test process capabilities for achieving higher H_2 purity levels as time allows. For instance, we expect that better separation of H_2 and N_2 can be achieved if the current nylon flow separator was switched to a Celgard separator with a much smaller pore size (one order of magnitude). Multiple options for the electrolysis gas products as described above will be evaluated and compared via the TEA model. We agree that the manual valve-switching operation currently being used to separate N_2 and H_2 is not practical for large-scale applications. This manual valve setup was intended to demonstrate the H_2 separation concept, but later in this project we will use automated solenoid valves, which are suitable for process upscaling.

4. The project will need to address the dissolved methane content, which is currently 50% of total production. Dissolved methane removal processes are not included in the experimental scope of the work for this project, but it has been included in the TEA modeling. The TEA and LCA presume use of a degassing membrane with the proposed D-LEWT process to remove 80% of dissolved methane based on published data from the U.S. Environmental Protection Agency. Note that the high fraction of dissolved methane was largely due to the timing of the work at the local wastewater plant, which mostly occurred during the winter season. This parameter will continue to be measured and is expected to be much lower during warmer-weather seasons.

5. Risk mitigation strategies are in place. Unclear which, if any, have been put into practice. Several technical risk mitigation strategies have been implemented to improve effluent water quality and reduce the rate of fouling in the AnMBR. Specifically, a biofilm support media was added to the anaerobic reactor to retain biosolids and reduce the fouling from suspended solids impinging on the cloth filter. Coagulants were dosed upstream of the membrane tank to promote floc formation and increase the removal of solids, phosphorus, and organics on the cloth filter. We also plan to incorporate adsorbents in the AnMBR system to further improve effluent water quality. Note that these adsorbents will be used with in situ bioregeneration such that they are only providing temporary removal of contaminants, and the final removal/conversion mechanisms are biological. Additionally, TEA and LCA work has been used to guide the research work. Results from this modeling work have been used to identify large material consumption and investigate options for reducing these inputs.

6. The additional chemicals (e.g., NaOH) impact on cost and LCA was discovered late and should be reflected in an updated risk register. The impact of this risk should be monitored closely, as it appears to be a higher risk than initially identified. We will add this item to our project risk register and set the risk level to moderate. Future experiments will focus on ways to reduce the amount of pH drop in the ammonia ion-exchange regeneration brine, such as draining the ion-exchange bed of water prior to regeneration. This will avoid unnecessary brine dilution and thus reduce the need for supplemental NaOH. It is true that earlier project work did not anticipate the large impact of NaOH chemical inputs on cost and greenhouse gas emissions. However, this issue and its importance are now clearly in view, and we will work to minimize the amount of NaOH needed. TEA and LCA work will continue to be used to understand the risk of this material consumption.

7. More information on how the membrane unit and the electrolysis system would be integrated into an existing anaerobic digestion platform would have been helpful. A membrane can be installed external to an existing anaerobic digester to filter the digester supernatant (effluent), which is currently sent to the head of the treatment plant. Plastic media and outlet screens to retain the plastic media could be added to the digesters to support attached biofilm growth, which will help improve membrane flux. The membrane will retain any effluent solids, which can be returned to the digester for additional digestion time. This decoupling of hydraulic and solids retention time will significantly increase the hydraulic capacity of an existing digester and improve digester effluent quality. However, ammonia will still pass through the membrane, and thus an ammonia ion-exchange and electrolysis process can then be used on the digester effluent. Early in the project, we proposed that this novel treatment train could be used to replace only the side-stream solids handling part of the wastewater plant. However, the impacts and benefits were relatively small in that case because it did not reduce the significant energy inputs for aeration in a mainstream conventional activated sludge process. More recently, we have worked to develop a retrofit alternative that would also convert the activated sludge tankage to anaerobic bioreactors by sealing them with flexible rubber covers and turning off the aeration. In this case, the whole plant could be converted to anaerobic treatment of the mainstream flow, which provides similar net energy benefits to a greenfield plant with AnMBRs, ammonia ion exchange, and electrolysis as proposed in this project (D-LEWT system).

8. Would like to see a material balance and a nitrogen species balance (especially soluble organic nitrogen). The concern is the total nitrogen exiting the process. We will provide a detailed nitrogen mass balance for our intermediate project review between BP2 and BP3. In the meantime, we will summarize here some key points about the fate of nitrogen in conventional wastewater plants and the proposed D-LEWT system studied under this project. Raw wastewater influent contains 20–70 mg/L of total nitrogen, roughly half of which is organic nitrogen, and the other half is ammonia. In conventional activated sludge processes, most of the organic nitrogen is converted to ammonia, and most of the ammonia is then converted to nitrate, with effluent total nitrogen typically ranging from 15–35 mg/L. (Some nitrogen is exported with the biosolids). To meet low total nitrogen discharge permits, a denitrification process is generally needed to convert some of the nitrate to nitrogen gas, which adds substantial cost but does lower the effluent total nitrogen to 2–12 mg/L, which again is mostly nitrate. In the proposed D-LEWT system, the AnMBR system converts most of the soluble organic nitrogen to ammonia, and the AnMBR permeate contains about 75% of the influent total nitrogen in the form of ammonia (15–55 mg NH_3-N/L). In the subsequent ion-exchange process employing clinoptilolite columns, up to 98% of ammonia is removed, providing a final effluent with total nitrogen concentrations of 1–2 mg/L, mostly as ammonia. Most of the captured ammonia is then released from the ion-exchange columns and converted to N_2 by electrolysis that is released to the atmosphere. All in all, the proposed D-LEWT process provides an attractive approach to providing effluent with low total nitrogen concentrations, but we have not yet characterized the relative amounts of soluble organic nitrogen and ammonia at the effluent or intermediate points in the D-LEWT system.

9. The cost of disposal for the waste sludge needs to be quantified, and the expected disposal option should be identified. Landfilling and land application of sludge are included in the current TEA and LCA models assuming a 20%/80% split between the two disposal options, respectively. Landfill tipping fees were assumed at $55/wet ton and land application costs were assumed to be $50/wet ton based on a biosolids survey of utilities in California. Note that land application costs in the Midwest are generally much lower (~$10–$40/ton), and these lower costs are being evaluated as a part of the TEA sensitivity analysis.

10. There should be a discussion on the life of the ion-exchange resin and fate of the spent resin. The lifetime of the ion-exchange resin is currently assumed to be 10 years, but we need to confirm this value based on the historical uses in other applications. Landfill will likely be the final disposal location for the spent resin and will be included in the TEA/LCA modeling.

11. The nitrogen control steps (ion exchange and electrolysis) are an important inclusion, and their value, if successful, is considerable, but relatively little information is provided to assess how efficient (with respect to yields and energy cost) and practical this part of the process is. So far in this project, the ion-exchange and ammonia electrolysis processes have been studied at lab scale, and the experimental results have met the related interim milestone targets. Specifically, multiple ion-exchange media have been evaluated and showed an ammonia removal efficiency of 80%, with potential for improved regeneration efficiency. For ammonia electrolysis, we have shown the ability to reduce ammonia levels in the regenerant brine by 85% with H_2 purity >93% v/v. The demonstrated performance of these processes has been included in the TEA/LCA work. As noted earlier, despite meeting milestone targets, these parts of the project have suffered the most from COVID-19 delays, and as a result we are requesting an extension to work on additional optimization and to better prepare for the upscaling and integration of these two processes into the pilot operations.

12. The AnMBR results presented are encouraging, but it is unclear if the biogas produced (>130 mL CH_4/g COD) meets the 85% COD value for biogas specified in the process description. The value of 130 mL CH_4/g COD represents the gaseous methane yield harvested in the headspace of the pilot cloth filter AnMBR operated during the late fall and winter seasons, when the process temperature was as low as 5°C and up to half of the methane produced was dissolved in the permeate (total methane production ~260 mL/g COD). These conditions represent the worst-case scenario for AnMBRs operating at ambient temperature, but still achieved a higher fraction of COD being converted to methane than the 30%–35% achieved with conventional activated sludge plus AD processes under much more favorable operating conditions. In addition, we have not yet implemented at the pilot scale several techniques shown to improve COD retention in the AnMBR system (e.g., coagulation and adsorbents). When included, these enhancements are expected to also improve COD conversion to methane and will support meeting the project goal of capturing 85% of available COD to methane.

13. The TEA and LCA results are very informative. The TEA project goal shows a significant cost improvement compared to the baseline AnMBR design, but curiously shows only a slight reduction relative to conventional wastewater treatment processes, which appears to be due to a notably higher chemical and overall CapEx cost. The production of more biogas and hydrogen while removing nitrogen in the D-LEWT process is a significant improvement over conventional wastewater treatment, but the limited improvement in overall cost and the fact that the product biogas is still relatively low in value reduces the magnitude of its impact. This project has the potential to dramatically increase the net energy production from wastewater treatment by both eliminating the significant energy inputs for aeration, while also increasing the energy outputs from biogas and hydrogen. This is a highly desirable outcome that would be a major paradigm change for the wastewater industry from a current significant energy consumer to a net energy producer. Our progress on the process costs should first be measured against the baseline AnMBR design, which is known to be higher than the current industry standard approach—conventional activated sludge plus AD. This is a common trade-off with bioenergy processes, especially nascent ones, where there is a higher price for reducing dependency on fossil fuels. We have identified a technical pathway to reduce the cost of the D-LEWT process to match the cost of the industry standard approach, which would be a rare and great success for bioenergy projects. To achieve cost parity with conventional activated sludge plus AD while also dramatically increasing bioenergy production from wastewater eliminates the typical trade-off with bioenergy projects and allows the industry to achieve better environmental outcomes without additional cost. Thus, this project can have a major impact without significantly reducing the baseline costs of wastewater treatment. The last point about the low value of biogas seems to suggest that because we currently have relatively inexpensive fossil energy

resources, it would be better to convert wastewater organics to higher-value coproducts. While economic optimization is a valid rationale, it seems to overlook that our society would still need low-carbon energy resources from some other source, and there is no guarantee that fossil energy prices will always be low. Even if it is not the highest-profit use of wastewater organics, having the option to make them into renewable energy resources at the same cost as traditional wastewater treatment would be a great option to have available.

A CATALYTIC PROCESS TO CONVERT MUNICIPAL SOLID WASTE COMPONENTS TO ENERGY

Worcester Polytechnic Institute

PROJECT DESCRIPTION

WBS:	5.1.3.202
Presenter(s):	Mike Timko
Project Start Date:	10/01/2018
Planned Project End Date:	12/31/2022
Total DOE Funding:	$1,995,199

Biofuels and bioenergy have the potential to reduce greenhouse gas emissions, improve energy security, and reduce energy price volatility. Unfortunately, despite significant progress in the past 20 years, conversion of biomass into transportation fuels is not yet directly competitive with fossil fuels. In fact, biomass conversion costs have decreased steadily in the past 10 years, as indicated by successive cost estimates published by NREL, while biomass feedstock costs have remained nearly unchanged. Reducing the costs of biomass production, transportation, and storage has proven more difficult. As suggested in DOE's Billion Ton Report, a potential solution to biomass production costs is to use waste feeds that would otherwise require a tipping fee for disposal. MSW, including food waste and green waste (e.g., yard waste), is especially attractive as a feed for bioenergy production because (1) depending on location, tipping fees; (2) conversion of MSW to energy diverts it from landfills, where its anaerobic digestion leads to greenhouse gas emissions; and (3) generation of MSW coincides with population centers.

Food waste constitutes approximately 15% of the total mass of MSW. Water constitutes approximately 70% of the total mass of food waste, effectively reducing its energy content relative to other organic components of MSW. Its high water content and variable composition make conversion using pyrolysis and gasification unattractive energetically, as these require energy-intensive drying and result in significant char and tar formation. HTL process is a great fit for these waste material feedstocks with high water content. This project is designed to tackle the main challenges associated with converting the combined food and green waste feed to fuel product, namely diesel.

The main project objective is to generate bench- and pilot-scale experimental data and models to de-risk commercialization of a process to convert a combined stream consisting of the food waste and green waste components of MSW into an energy-dense bio-oil and refined lignin stream. The primary components of the process include a solvent separation step to remove lignin (a potentially recalcitrant component) from the green waste stream to generate a delignified biomass stream; an HTL step to convert the food waste and holocellulose stream into a raw bio-oil; a catalytic upgrading step to increase bio-oil yield and/or improve its composition; and a catalytic hydrogenation step to reduce oxygen and nitrogen content of the bio-oil to further improve its composition. These component processes will be investigated at the bench scale and the data used for operating a pilot-scale system constructed at Mainstream Engineering. Finally, the economics and life cycle analysis of the carbon emissions from the overall process will be continuously assessed using standard metrics of energy return on investment and levelized cost of energy.

A multi-university and industry team has been assembled with expertise in biomass pretreatment, high-pressure processing, catalysis, and reaction engineering. The project is split into eight tasks based on the individual expertise, with milestones for each task.

The main products of the technology will be upgraded HTL bio-oil and a purified lignin stream. Byproducts will include a gas purge stream, consisting primarily of carbon dioxide; a char stream, which will qualify as a class A bio-solid; and an aqueous phase containing water-soluble organic compounds produced in the hydrothermal liquefaction process. The catalytic upgrading process is designed to minimize carbon loss to the aqueous phase, since aqueous-phase carbon represents energy loss and the contaminated aqueous phase must be treated prior to discharge, thereby increasing costs and decreasing overall efficiency. The catalytic hydrogenation step further improves HTL bio-oil properties, specifically heating value, by rejecting oxygen and nitrogen.

The target market is the U.S. diesel fuel market for the upgraded bio-oil product. This market represents a billion-dollar opportunity in both transportation and stationary heat and power. The feedstock of municipal solid waste is around 250 million tons per year in the United States. Utilizing the organic fraction (~40%) would significantly divert waste from landfills while providing an inexpensive and renewable feedstock for fuel production. It is estimated that the proposed technology could produce 10%–15% of the annual domestic gasoline usage (assuming 100% material efficiency) in energy-dense oil product or 3%–5% with 25% efficiency. Additional products from this waste conversion process include a high-grade lignin separated from green waste, which has an additional value.

The primary challenges to the success of bringing this technology to commercialization include producing sufficient bio-oil yield and energy quality, handling and stability of bio-oil products for upgrading, catalyst stability in long-term usage, and successful fractionation of lignin from complex real feedstocks.

The carbohydrate fraction of green waste has been successfully separated form lignin component using optimized cosolvent pretreatments. To meet the bio-oil quantity and energy recovery, hydroxyapatite catalyst was found to significantly improve bio-oil yields from food waste feeds while maintaining good hydrothermal stability. Handling of viscous bio-oil and the thermal stability oil products during upgrading requires selection of appropriate solvents and separations prior to processing.

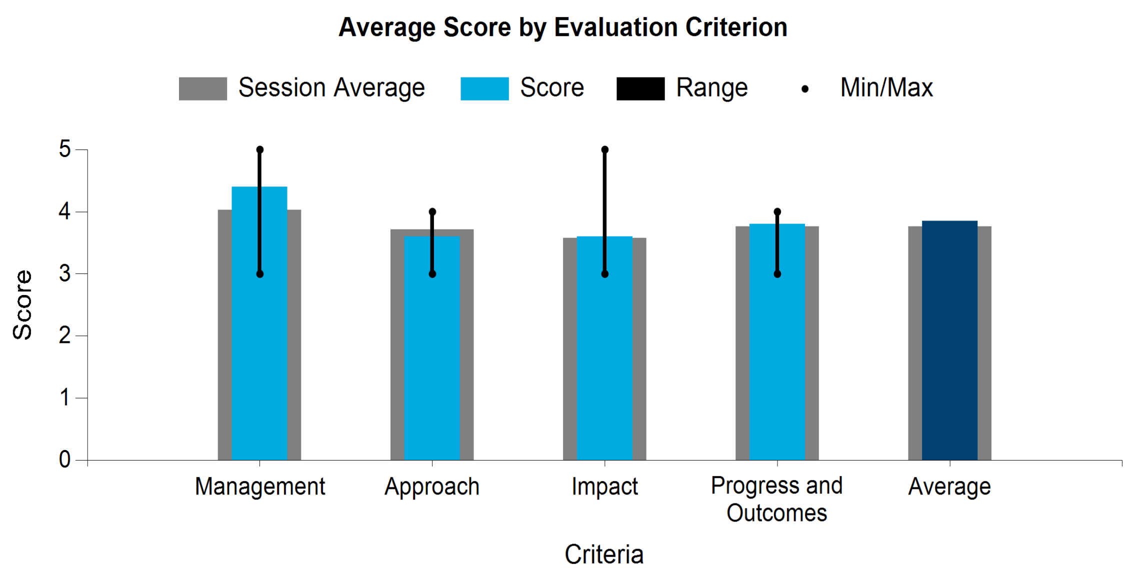
In addition, the COVID-19 pandemic has created unforeseeable challenges to the progress of the process due to laboratory work restrictions, researcher illness, and researcher absence due to contact tracing. The prolonged shutdown resulted in coking in the upgrading reactor, which then required many weeks to rebuild. Sourcing real food waste during the pandemic is problematic due to the additional risk to waste handling and the shutdown of most cafeterias. We did source approximately 20 lb prior to the start of the pandemic. Fortunately, sufficient supplies of green waste and limited waste were procured prior to the pandemic.

To date, we have successfully fractionated real green waste into lignin-rich and carbohydrate-rich fractions for lignin products and biofuel feedstocks, with the carbohydrate fraction having less than 20% lignin. This has partially met milestones, with further optimization of reaction parameters required to increase the purity of the lignin fraction to >80% and remove ash content. Carbohydrate and lignin fractions have been then evaluated using hydrothermal liquefaction, showing that lignins provide ~40 wt % yield of bio-oils, while carbohydrate fractions yield ~20% bio-oil. Further optimization of the reaction parameters for HTL is underway to optimize the yield from the different fractions. In parallel, we have launched machine-learning efforts to understand the relationship between feed properties and HTL biocrude yield, crucial to commercial implementation of complex and time-varying feeds.

We have screened many catalysts for HTL of food waste to bio-oil, including waste materials such as red mud, clay, and fly ash; and oxides such as ceria, zirconia, and ceria-zirconia. Basic oxide catalysts such as red mud were shown to be highly active for conversion of food waste to bio-oil, although exhibited poor stability. In addition, nickel was supported on oxides (Ni/CeO_2, Ni/ZrO_2, and $Ni/CeZrO_x$); catalyst showed a dramatic reduction in char yields with the highest bio-oil energy recovery (39%). A new catalyst, hydroxyapatite, has been utilized to significantly improve bio-oil yields and energy recovery from the HTL of food waste, meeting current milestones. Hydroxyapatite is a bifunctional catalyst with basic and acid sites, and we have determined it is hydrothermally stable for 200 hours at 300°C. Catalytic HTL of food waste to bio-oil using hydroxyapatite has exceeded the milestone of 45% energy recovery. Kinetic studies are underway to optimize bio-oil yields from this catalytic hydrothermal process.

Upgrading the raw hydrothermal bio-oil to a fuel-compatible composition requires further reducing the oxygen and nitrogen content. This is achieved using hydrogenation step. We have utilized Mo_2C catalyst for hydrogenation of hydrothermal bio-oil. More than 75% of the oxygen and nitrogen has been removed from hydrothermal bio-oil produced from food waste, from dilute (1 wt %) solvent stream. An upgraded oil with <9 wt % oxygen and 2 wt % nitrogen has been realized to date, close to the required milestone. Work is ongoing to increase the bio-oil feed concentration and to study the catalyst stability.

A continuous pilot-scale catalytic hydrothermal reactor was constructed and operated for >10 hours at Mainstream Engineering using food waste feed, ahead of schedule. Using techno-economic analysis, the minimum fuel selling price of the fuel energy produced using the best catalyst and feed rate optimization is $3/GGE (including $1/GGE upgrading) for this overall process, without taking into account transportation costs. This far exceeds the current milestone of $4.83/GGE.



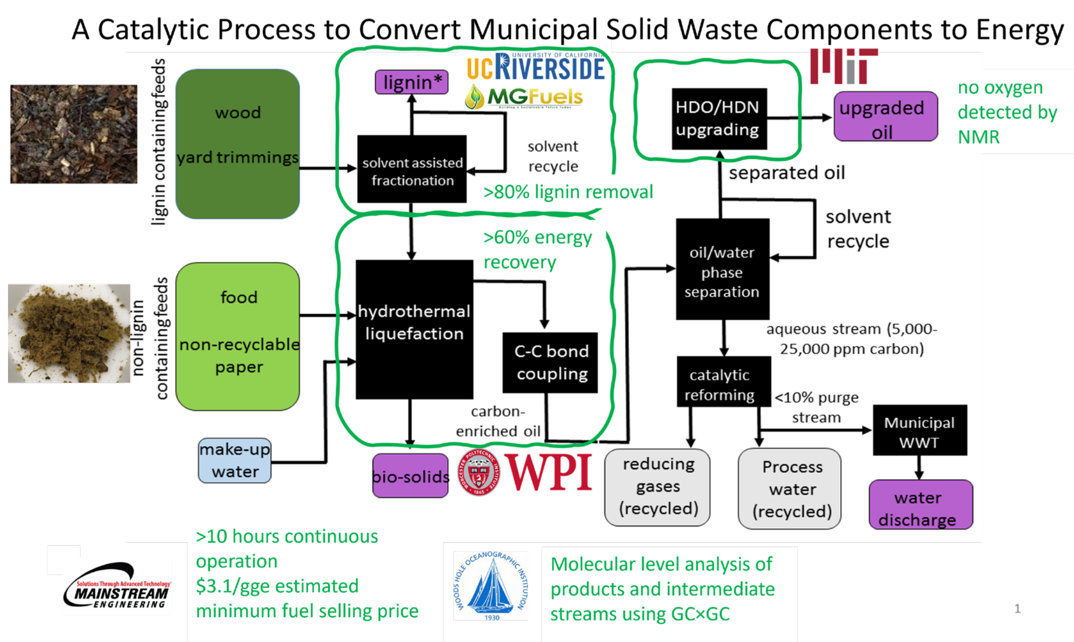


Photo courtesy of Worcester Polytechnic Institute

COMMENTS

- Might avoid using the term biosolids for the solid inert material that falls out of HTL. Just less rules/concerns than if it is called a biosolid. Extensive use of milestones and quantitative goals. Doing a great job of tracking progress against these values. Are going to miss some of the intermediate targets (e.g., MFSP), but will have made substantial progress on many others. Seem to have hit some stretch milestones early with some good research choices. Team seems to be communicating well, and clearly articulated the challenges that COVID-19 has placed on the team. Team accurately communicated the level of risk/uncertainty, as well as presented reasonable mitigation plans. The project is still a bit early relative to others in the commercialization process, and may have a bit of trouble bridging the valley of death. Scale and runtime are accurate for the scale, but are still well removed from commercial relevancy. This team is engaging with critical commercial partners, including oil company Phillips 66. Have assembled a strong advisory board. Are using the PNNL HTL work/TEA to help better position this work with the other work that has been done in the HTL space, particularly the work that has been funded by BETO. Team is engaging with other DOE-funded work and with the larger scientific enterprise.

- Strengths: Strong multi-industry partnerships from research organizations and commercial partners. Structured engagement of commercial partners from each stage of the value chain. Clear research approach. Differentiated from other HTL research projects and influenced by industry advisors. Strong understanding of regional needs and evidence of adapting research efforts to match these needs (e.g., identification of aviation gas needs). Valuable progress on commercially viable catalyst (hydroxyapatite).

  Weaknesses: Currently not including tipping or transportation fee. Will be critical to include this in model (there appears to be plans to adapt the model to include this). It was difficult to determine what scale the catalyst work was being performed at and the scale-up challenges that would arise as the technology transitioned to more commercially relevant scales. In light of COVID-19, it would be valuable to explore the health and safety risk of transporting and handling large volumes of waste at commercial scale. Understanding the cost of processing waste with high soil content or the cost of treating the feedstock to remove soil will be required.

- The management appears to be fine. The advisory board is particularly strong. The presentation was very unclear. There were aspects of the flow chart that was presented that were unclear and appeared to be undecided at the present time (for example, whether the upgrading was in situ or ex situ, how the green waste entered into the overall process). The presence and characteristics of waste streams that come from the proposed process are not clear, nor are the challenges that they may present. This should be incorporated into the TEA/LCA and into the flow chart. The most progress appears to have been made in the area of the catalyst use, which appeared to be strong. The scaling up of the system earlier than expected is also very good. The ultimate goals regarding mixing the yard waste and food waste were unclear. It seems that "pure" feeds are being used at this point, but again, that was not clear.

- The project results to date are encouraging and they are meeting most of their milestones. They have a very diverse advisory team, which is a benefit on this type of project. One concern is the problem they encountered with the food waste slurry and having to use dried waste. As the scale increases, using a dried feedstock may be impractical. I think it is important to understand why there was a problem with the waste slurry and how that can be changed moving toward full-scale processes. Would like to see a mass balance and a discussion on the waste streams produced and how they can be disposed or issues with disposal. Also a discussion on the potential impacts of recycle streams to the WRRF relative to nutrient removal or other permit or operational effects.

- This project looks to improve overall performance of HTL technology to convert a specific fraction of municipal solid waste (the food and yard waste portion) to liquid hydrocarbon fuels. The project management appears sound and the use of and composition of the advisory board is outstanding. These companies, representing all of the key areas that intersect in this project (e.g., food waste source, waste management, refinery, HTL commercial company), should help guide the research and ensure that the project remains focused on real-world issues and constraints. The approach concentrates on certain parts of the overall proposed process and is generally reasonable, though not all tasks appear to be of equal value. It is not clear what the innovation is in the lignin fraction portion of the project or how it has been successful, but it is also not clear why it is needed. HTL has been successfully demonstrated on wood feeds in the past without having to remove lignin, and it is not obvious from the results presented that lignin removal is worth the additional steps and process complexity. While the use of catalysts in HTL tests adds to the process complexity, the ability to grow carbon chains to ensure that more carbon stays in the oil phase instead of the aqueous phase and the resulting higher biocrude carbon yields is impressive. This may signify a key advantage to catalyst use and possibly be a game changer, especially when the target feed is mostly six-carbon carbohydrate species as opposed to longer-chain lipids that are more likely to stay in the product oil phase on their own. The upgrading results presented are not that impressive to date. The milestone of demonstrating less than 9% oxygen in the upgraded oil sets the bar much too low. Current hydrogenation technology can easily achieve the required target of less than 1% oxygen for acceptance by a refinery, so it is not clear what exactly has been accomplished in this task to date. The construction of a continuous HTL pilot plant will be useful if it represents a fully integrated version of the proposed process. The TEA is modeled after that developed by PNNL, and the results presented with respect to MFSP of the fuel product appears to be comparable to that presented by PNNL. While this is encouraging on the one hand, it is not clear how this project's TEA distinguishes itself from that of PNNL and whether this is an unnecessary duplication of effort. Some of the stated TEA assumptions (e.g., no tipping fees or transportation costs) are not realistic, and a base case nonzero value should be included in the model. The impact of this project in advancing HTL technology and the development of liquid hydrocarbon fuels is significant and entirely consistent with BETO's objectives.

PI RESPONSE TO REVIEWER COMMENTS

- We appreciate the reviewers' time and effort to help improve our BETO project. Overall, reviewer comments are very positive, with the apparent bottom line conclusion being: The impact of this project in advancing HTL technology and the development of liquid hydrocarbon fuels is significant and entirely consistent with BETO's objectives. Positive comments include, "the ability to grow carbon chains to ensure that more carbon stays in the oil phase instead of the aqueous phase and the resulting higher biocrude carbon yields is impressive. This may signify a key advantage to catalyst use and possibly be a game changer," "The project management appears sound and the use of and composition of the advisory board is outstanding," "The scaling up of the system earlier than expected is also very good," and "The project results to date are encouraging and they are meeting most of their milestones."

  While the strengths appeared to outnumber the weaknesses, some weaknesses were identified. We respond to the most substantive criticisms here. If we have overlooked a comment that BETO deems substantive, we will be happy to provide a specific response to it. Progress on hydrodeoxygenation was flagged as lagging. Since the time of the Peer Review, we have prioritized this area and made substantial progress. Our latest results using the Mo_2C catalyst indicate quantitative removal of all nitrogen and oxygen compounds that can be detected using 2D nuclear magnetic resonance. We are waiting for elemental analysis of the corresponding upgraded oils and currently anticipate that they will meet or exceed BP2 milestones. Moreover, this new result was obtained from biocrude resulting from hydrothermal processing of an Army surrogate food waste mixture that results in a highly viscous, tar-like substance. The tar-like substance is difficult to process, which has necessitated substantial effort to enable its study under upgrading conditions. Subsequent work on hospital food waste and prison food waste, described later in this response, produces a less viscous biocrude that should be much easier to work with than the tar-like biocrude obtained from the Army surrogate mixture. We plan to evaluate upgrading of the prison food waste and hospital food waste biocrudes in the next several weeks.

Several reviewers expressed concern about feed selection and procurement. At the time of the review, we had already evaluated hospital food waste, both in batch and continuous processes. The hospital food waste is available dry, which is a distinct advantage for an R&D project since the dry feed is easily frozen and stored to provide a single source with stable characteristics. The commercial process will not utilize dried feeds, and we recommend establishment of a wet-waste bank, similar to the one at Idaho National Laboratory for biomass, to standardize research in this area and take the burden off technology developers to procure and characterize their waste streams. One aspect of the wet-waste bank would be to evaluate the effect of drying on yields obtained from different conversion processes, namely HTL and AD—and potentially others as they reach sufficient levels of maturity. Since the time of the Peer Review, we secured approximately 10 kg of undried prison food waste with help from PNNL. The prison food waste is sufficient for all immediate needs, and we have already evaluated HTL processing of prison food waste. We find that the biocrude yield is >50%, with the second stage of catalytic upgrading of the aqueous phase contributing approximately 10 percentage points to this yield. Processing of hospital food waste results in 40% biocrude yields (by total mass); addition of green waste does not detract from the biocrude yield obtained with hospital food waste, provided that the green waste is present at loadings less than 25 wt %. For BP3 activities, advisory board member Republic Services can provide tons of food waste, as necessary. One challenge with using a different feed for batch and continuous tests is different biocrude yields arising from the different compositions. In parallel with experimental efforts, we are finalizing a machine-learning regression analysis of more than 500 published data points to predict biocrude yield from composition information. We will use this regression to target conditions of specific interest for experimental investigation and to predict performance of new waste streams necessary for continuous tests in BP3.

Some concerns were raised about the TEA, the relationship with previous work done by PNNL, and the inclusion of a food waste tipping fee. This comment likely results from a lack of clarity on our part. We have used the PNNL TEA of the HTL process as a starting point, duplicating none of their effort. We then did several analyses: (1) replaced key data with our results to evaluate the response of MFSP to new technology, (2) added costs associated with the catalyst, (3) analyzed effects of learning rates and transportation on optimal HTL scale, and (4) implemented more rigorous methods to capture technological uncertainty. Due to the constraints of the Peer Review, we were not able to explain all of these activities in depth. However, each of these activities has added value to the original work done by PNNL, without—to our knowledge—duplicating any of it. As for including the food waste tipping fee, members of our advisory board have advised us that a cost on the order of $25/ton is likely to be representative, a figure that includes tipping fee and transportation. At present, we have not included the tipping fee in our analyses for the simple reason that our focus has been on the effects of technological improvements on MFSP. Decreasing MFSP by changing a cell in an Excel worksheet would not capture technological improvement, even if the resulting cost would be more representative of what we can expect. In the future, we can report both values—i.e., with and without the tipping fee.

DEVELOP AN EFFICIENT AND COST-EFFECTIVE NOVEL ANAEROBIC DIGESTION SYSTEM PRODUCING HIGH PURITY OF METHANE FROM DIVERSE WASTE BIOMASS

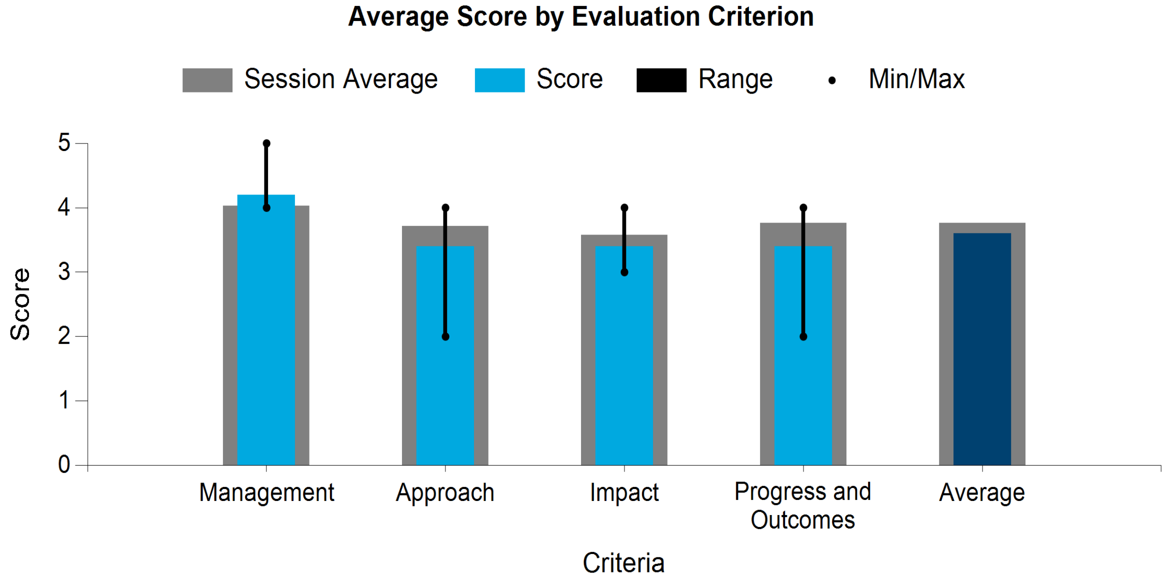
Washington State University

PROJECT DESCRIPTION

WBS:	5.1.3.204
Presenter(s):	Shulin Chen
Project Start Date:	10/01/2019
Planned Project End Date:	09/30/2023
Total DOE Funding:	$2,273,052

The lack of cost-effective AD technology is a major hurdle for converting organic wastes to RNG. This project aims at developing a novel AD system to increase methane yield, productivity, and purity through process intensification. This system takes the synergistic advantages of innovative process engineering and thermophilic anaerobic microorganisms to: (1) overcome the recalcitrance of waste biomass through hydrothermal pretreatment, (2) enhance biological conversion rates by using hyperthermophilic microbial communities, (3) perform in situ purification of biogas through methanogenesis under pressure, and (4) relieve inhibition by recovering ammonia as fertilizer. This novel system is expected to have a near-term commercialization potential by significantly reducing the cost of biogas-based RNG production. The project team includes Washington State University, Pacific Northwest National Laboratory, Regenis LLC, and DVO, Inc. The active participation of the industry partners makes it possible to use existing AD systems as baseline technology and fast technology transfer and commercialization of the novel technology.

The project is expected to produce significant impacts. The proposed novel AD system offers a new platform to DOE’s technology portfolio for production of RNG from different types of organic wastes. The project results will lead to critical data for advancing the technology from technology readiness level 3 to 5, decreasing the risk factor in commercializing the technology. Success in this project will remove several key technical barriers and lead to economic development opportunities by creating values from the immense amount of waste biomass. The project also benefits the federal government, as this effort aligns well with the priorities of several governmental agencies, especially those of BETO.



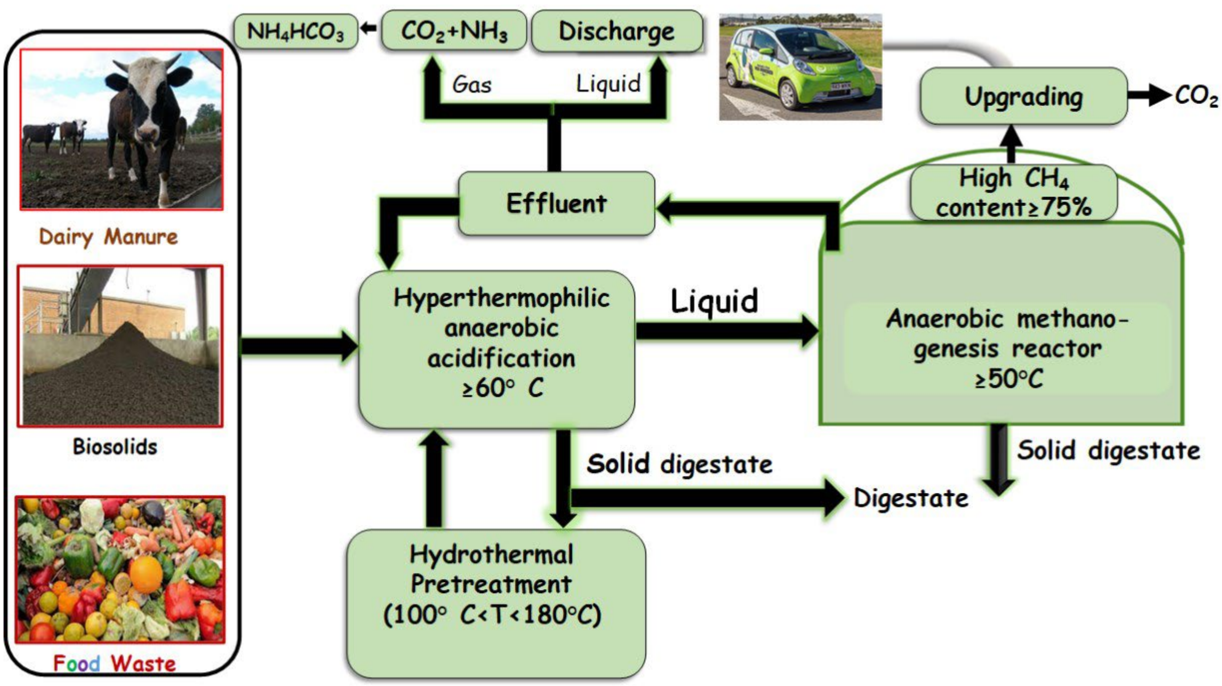


Photo courtesy of Washington State University

COMMENTS

- Good management plan. Risks and risk mitigation strategies were identified. Would like to see a process flow diagram and mass balance. Would like an explanation of what "highly severity conditions" means as it relates to the dairy waste disintegration. The biogas yield is specified relative to volatile solids, but I am unclear as to whether that is volatile solids fed or volatile solids destroyed. If there are any recycle streams to the WRRF, they should be identified.

- Progress is appropriate for a project that just got started. Work seems to be preceding at the scheduled rate. Project has engaged with good commercial partners and appears poised to transition work out of the laboratory and into the marketplace. Could spend a bit more time clearly aligning goals with those stated by BETO; minor quibble. Performer is tackling critical challenges in the continued commercialization of AD technologies. Industrial partner is providing operational data, and appears to be actively involved in this project. Feedback loop is tight (in a good way). Seem to have a strong management team and plan in place. Reasonably discussed their risks. Were quite candid throughout the presentation, which bodes well for the communication needs that will arise throughout this project. Early work has been on manure (building on DVO's expertise), with subsequent moves to biosolids and food waste as elements of the feedstock. Ultimately, this is quite early in trying to adequately judge this project, but project seems to be well positioned at this early stage.

- Strengths: Strong interdisciplinary team with value-add industry partners as consultants. Sound communication plan with all research parties. The project appears to bring a novel approach of combining hydrotreating with thermophilic anaerobic digestion for enhanced methane production. Valuable advancement of fibrous treatment for increased carbon availability in biogas upgrade.

  Weaknesses: It would have been valuable to discuss the scale-up challenges that are likely to arise and how the research team would work to mitigate these risks through the project (e.g., the challenges of integrating and running continuous thermophilic digestion at scale). There is concern that the incorporation of energy-intensive unit operations (e.g., hydrotreating, thermophilic digestion) will result in prohibitive economics for commercial application. It is encouraged that the industry partners are leveraged for validation of the process economics for determination of viability (due to high operational cost expectations).

- The project just started about 4 months ago. The management approach is clear. It sounded like the addition of Basecamp for project management has come since the project started; hopefully this is not an indication of management issues. The involvement of industry partners is excellent and will enhance the relevance of the project and the use of the results. The results are impressive for such a recently started project. There is definitely work to be done, but it is good to see things starting well.

- This project aims to improve the methane yield and reduce the retention time of AD for various waste feedstocks while also managing the fate of nitrogen. The management appears to be appropriate, and it is good to see the inclusion and participation of important and relevant industry partners associated with designing and installing digesters. Their assistance should help guide the research and hopefully will allow a more credible path to incorporation of any experimental success within commercial applications. The general concept behind this project is understood and commendable (particularly the attention given to ammonia recovery), but there are many details that are missing. The specific tasks for this project are not clearly stated, although the cost, yield, and residence time metrics are clear. There are no photos, diagrams, or descriptions of the experimental setup or what specifically is being done. The system is described as being novel, but it is unclear exactly what it consists of or what the novelty is—for example, is it the hyperthermophilic microbes or the reactor(s) design? Similarly, it is good to see some results already only a few months after the project start, but it is difficult to verify the claims made based on the data shown. Graphs and legends in several cases were not adequately labeled, making it hard to interpret the message. Also, milestones are given in terms of a concentration, but the supporting data shown are as a percent recovered (or vice versa), making it difficult to confirm achievement. The future work slide is not sufficiently detailed. The overall impact of this project is moderate; the increased yield and reduced retention time will be significant if successful, but the lack of ability to retrofit existing AD plants may slow implementation, and the ultimate biogas product is of relatively low value from the perspective of BETO's mission.

PI RESPONSE TO REVIEWER COMMENTS

- The research team thanks the reviewers for the constructive comments. The research team concurs with the panel on the challenges of scale-up and integration of the system and will capitalize on the experience and expertise of the industrial partners in addressing these challenges. The team will include as much as possible specific tasks, descriptions of the system, energy and cost analysis, and discussions about the data obtained in future presentations and reports.